2016 WPI/IIT Project Center: Annual Report

Kamand, Himachal Pradesh, India

March 15—May 3 of 2016

Welcome from the Project Coordinators

The Indian Institute of Technology (IIT-Mandi) and Worcester Polytechnic Institute (WPI) from Massachusetts, USA are pleased to present the work from our 2016 joint Project Center teams. Since 2013, the Center has united 3rd year undergraduate science and engineering students from each institution to collaborate on projects featuring complex design challenges that emerge from the interplay of environment, technology, and society.

Beyond our cross-cultural engagement, our partnership is meant to teach students how to engage stakeholders in the design process, and to influence the tendency of policy makers, designers, and scientists to simplify social conditions. Over-simplification reduces complex, locally specific challenges to targets that should quickly be fixed with the right technology. However, technical solutions applied without the full understanding of the social context will more likely generate unintended or negative consequences. The end result might be expensive, environmentally damaging, difficult to sustain, and ultimately abandoned. The Interactive Socio-Technical Practicum (ISTP) encourages student teams to frame interaction with communities as a learning experience and as a cooperative process. In this course, students exchange ideas with their peers across international boundaries, they build experience working in teams, and they explore complexity in social arenas relevant to their projects. This experience provides an extraordinary opportunity to develop the empathic skills necessary for appropriate policy or design decisions as future engineers and scientists working in the world today.

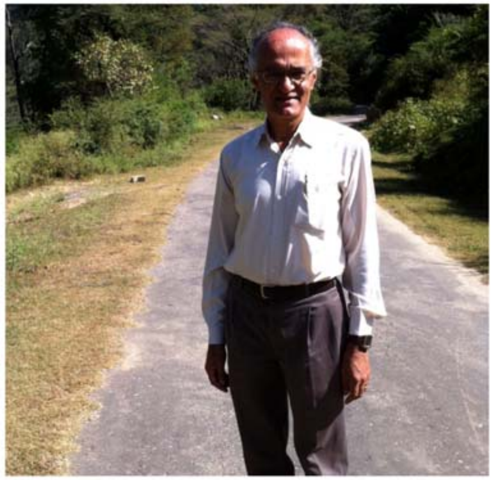
During our time onsite at IIT Mandi, the 7 student teams investigated improved designs for traditional cook stoves, evaluated solar street lighting, expanded local rainwater harvesting, devised lightweight origami shelters, evaluated strategies to communicate risk of landslides, improved solid waste management strategies, and enabled better communication between healthcare facilities. They conducted interviews, surveys, field-tests, and assessments. To that end, we wish to acknowledge the dedication and long hours of guidance from the faculty mentors that worked closely with each team through completion.

As always, the WPI cohort is deeply grateful to our hosts and coordinators at the beautiful Kamand Campus of the IIT Mandi. We are touched by the welcome and support we receive each year from coordinators, teaching assistants, support staff, faculty members, and fieldwork participants that enable these studies to continue. In particular, we wish to thank the Director, Professor Timothy Gonsalves, for his continued appreciation for the vision put forth by this Center.

Dr. Venkata Krishnan, Dr. Stephen McCauley, Dr. Devika Sethi, Dr. Ingrid Shockey, Dr. Dericks Shukla,
Project Center Coordinators 2016

Greetings from the Director of IIT-Mandi

The WPI Project Centre at IIT Mandi has been running smoothly since 2013. This year, we've seen the successful conclusion of the 3rd joint ISTP-IQP projects. Over the years, these joint projects by students of WPI and IIT have explored assorted technological interventions in the villages and towns surrounding IIT Mandi. These projects have built up a valuable corpus of knowledge and experience. Related initiatives by NSS on education for village children and the opening of the IIT Mandi Takshila School are opening the doors of opportunity to the residents of the Kamand area.



With these initiatives, expectations of improvement in living standards are growing in the villages of the region. The challenge before us is to translate some of the ideas generated in ISTP and related courses such as Design Practicum and Major Technical Project into widely-used, sustainable technologies and products adopted by villagers of the Himalayas. For example, an idea on livelihood issues of village women was explored by ISTP teams over 2 years. Subsequently, it has been taken up as an MTP to develop a portal accessible by mobile. Now, it is a funded project and by the end of 2016, village women are expected to be getting part-time employment and skill development opportunities through its portal.

This year, IIT Mandi has started the IIT Mandi Catalyst, an independent Section 8 company whose goal is fostering and incubating businesses promoted mainly by IIT students and faculty to provide technological solutions and products for the local communities. IIT Mandi Catalyst has received generous funding from the Department of Science and Technology complemented by incubation space etc from IIT. It is our expectation that some of the ISTP projects will fructify into rural-focused business enterprises under the aegis of Catalyst.

Best wishes to all teams who have participated in the Open House on 1st May 2016, and congratulations to the award-winning teams. I'm sure that your careers will benefit greatly from your unique experience in the ISTP-IQP. Thanks to the faculty from WPI and IIT Mandi whose tireless dedication to this unusual concept is responsible for its success.

Timothy A. Gonsalves
Director, IIT Mandi
26th April 2016

The reports in this booklet represent the work of WPI and IIT undergraduate students. For more information about the project center, see:

http://www.wpi.edu/academics/igsd/iqp.html

Or at the IIT's ISTP page:

http://www.iitmandi.ac.in/istp/index.html

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Improving Landslide Risk Communication in the Mandi District

Abstract

Our goal was to develop, evaluate, and improve landslide risk communication strategies in Mandi, a region affected by pervasive landslides. Policymakers, scientists and village residents were interviewed to understand how the stakeholders experience landslides. We determined the key gaps in knowledge, specifically regarding landslide causes and signs, the residents' perceptions of risks and the hazard maps, and the current communication strategies. We developed an educational plan and an SMS-based risk communication system that includes early warning system and informational messages.

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Landslides in Mandi District

Landslides are feared in mountainous regions for their unpredictable and highly destructive forces that result from downward and outward slope mass movements. The District of Mandi, located in the heart of Himachal Pradesh, northern India, is prone to frequent and pervasive landslides. Shown in Figure 1 below, this region has a diverse terrain ranging from hills to mountains, with major river systems cutting through the valleys.

Figure 1. Mandi Town, Himachal Pradesh

Natural hazards such as monsoonal rains, harsh winters, and earthquakes make the region vulnerable to landslides, and human activities such as farming and forestry practices, animal grazing, and road construction exacerbate these natural conditions.

In order to mitigate the impact of landslides in prone areas, effective risk management and communication are necessary. Risk communication strategies generally aim to provide stakeholders with information to reduce risk, to respond to an event, and to recover afterwards. Currently, there is no universal solution to managing landslide risks; however, adaptations of early warning systems (EWS), which detect factors that indicate potential disasters and communicate the risk information to the affected parties, have been the most effective risk communication strategy. Nevertheless, EWS and other landslide risk communication strategies are controversial because their poor implementation in communities has led to numerous social, economic, and environmental issues. As a key topic at the Third United Nations World Conference on Disaster Risk Reduction in 2015, landslide risk communication initiatives were outlined to educate vulnerable communities about the causes and consequences of landslides, and to promote awareness of the warning systems and risk management in place.

Although the Himachal Pradesh government has formulated a Disaster Management Plan, an effective risk communication strategy does not currently exist. The deficient communication between stakeholders about the prevalence and hazards of landslides increases the associated risk. The goal of this project was to develop, evaluate, and improve landslide risk communication strategies in the Mandi District. In order to reach our goal, we assessed the current conditions in the district to generate a baseline assessment, collaborated with stakeholders to understand how they experience and confront landslides, and developed and evaluated a landslide education program and a technical communication solution specific to the Mandi region.

Landslides: Causes and Communication

In this chapter, we address the key elements of risk communication and the terminologies associated with landslides, and evaluate early warning systems through case studies.

Causes of Landslides

There are two main causes of landslides: natural and human causes, both which can lead to landslides that damage life and property. Examples within each category of landslide causes can be found in Table 1 below.

Table 1. Causes of Landslides (Landslide Types and Processes, 2013)

Natural Causes	Human Causes
•Prolonged rainfall	•Deforestation
•Earthquakes	•Animal grazing
•Soil composition	•Construction

Two reports detailing the fundamentals of human-caused landslides are described in the Background section of the Supplemental Materials found on the WPI and IIT websites.

Risk Assessment and Risk Communication

Risk assessment is used to identify potential hazards, including landslides, and analyze possible outcomes in the event that a disaster occurs. If the risk assessment made by the stakeholders results in an improper response to the situation, the stakeholders then become more vulnerable to the risk. Oftentimes, the stakeholders' response is dependent on their perception of risk, which can be influenced by culture, experience, and education. Thus, it is critical to assess the stakeholder's perception of the risk at hand before considering technical solutions (Breakwell, 2014; Patra, 2015; Devi, 2015).

While landslide risk assessment involves analyzing possible outcomes of landslides, risk communication involves the dissemination of this prediction. It is important to understand the type of risk that an area experiences in order to create an effective risk communication strategy. In India, there are many agencies and non-governmental organizations (NGOs) that attempt to provide tools for better risk assessment and communication through methods such as landslide hazard zonation mapping. Early warning systems have been successfully used as a risk communication strategy to mitigate the effects of landslides in mountainous regions by providing warning information with sufficient time to reduce damage. Sättele et al. (2015) categorize three classes of EWS: alarm system, warning system, and forecasting system. These classifications are determined by the systems' function of automation, and their characteristics are shown in Table 2.

It is important to establish warning criteria describing when, how, and to whom an EWS should distribute a warning. These criteria can ensure proper communication between stakeholders and fulfillment of responsibilities, so that the risk communication strategy does not become ineffective and cause further damage (Cloutier, 2015). An example of assigned responsibilities for each stakeholder is shown in Figure 2.

Table 2.Characteristics of Early Warning Systems, adapted from Sättele, 2015

Alarm System	Warning System	Forecasting System
•Autonomous	•Semi-autonomous	•Non-autonomous
•Detect on-going process	•Detect precursors	•Detect precursors
•Short lead times	•Extended lead times	•Extended lead times
•Threshold	•Threshold + expert decision	•Expert decision

Figure 2. Example of responsibilities assigned to each stakeholder in an EWS

Case Studies on Early Warning Systems

We compare four case studies from Japan, China, Malaysia and Mexico that address how each country implemented an EWS for natural disasters. Each case study pertains to our site because of the similar geography, climate, and causes of landslides. These case studies are summarized in Table 3.

Table 3. Summary of the Japan (Natural Hazards Observer, 2008), China (Wen, 2005), Malaysia (Abdullah, 2013), and Mexico

	Problem	EWS Solution
Japan	Tectonic plates à earthquakes	Ground sensors + education
China	High rainfall à land-	Rain level
Malaysia	High rainfall à landslides	Rain level + education
Mexico	Deforestation à landslides	Residents + experts

Information from each case study was utilized to help develop an effective risk communication plan for the Mandi District. In order to create an effective risk communication strategy for landslides, it is important to consider the stakeholders' risk assessment and the components of a communication strategy. For our site's location, the constraints of the EWS include Mandi's location in a mountainous region with rivers and intense rainfall, combined with improper road construction due to more tourism in the region, increasing the district's susceptibility to landslides.

Methodology: Data Collection and Prototype Development

In order to develop, evaluate and improve risk communication strategies in Mandi District, we established three objectives outlined in Figure 3.

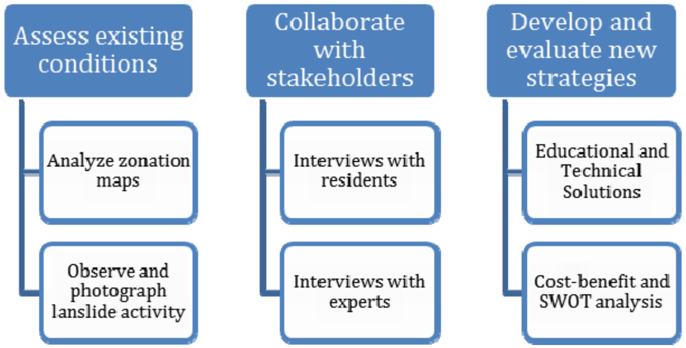

Figure 3. Project objectives and associated strategies

Our first objective assessed the current conditions in Mandi District. To determine the locations of the villages to visit for interviewing, we utilized the landslide hazard map from the National Remote Sensing Centre. This map and its corresponding key are shown in Figure 4.

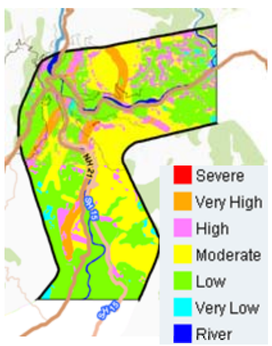

Figure 4. Landslide hazard map of Mandi and surrounding areas (Bhuvan, 2015)

In order to obtain a selection of village regions with varying levels of landslide hazard, we identified the coordinates of locations with various hazard levels using the GPS coordinates feature on the landslide hazard map. The GPS coordinates were then applied to Google Maps to determine the identity of the villages in the selected locations. The list of village regions we visited is: Katindhi region (low risk), Dudar region (moderate risk), Nela region (high risk), and Khaliar region (very high risk). The map of their locations is located under the Methodology section of the Supplemental Materials on the WPI and IIT websites.

When traveling to the villages, we recorded any signs of recent landslide activity by taking photographs in order to gather visual data about the prevalence of landslide activity in the area. Additionally, we visited the remnants of a landslide near the IIT-Mandi Kamand Campus.

To understand the stakeholders' perceptions of landslides and risk communication, we conducted interviews with three stakeholder groups: policymakers, scientific experts, and residents. When interviewing village residents, we employed a semi-structured interview style. If the interviewee did not speak English, our IIT teammates conducted the interview in Hindi and their responses were translated into English. Through the interviews with the residents, we were able to evaluate their initial understanding of the causes of landslides and prevention measures, their perception of landslide hazard in the area, and their access to technology and preferred methods of warning. To gauge the residents' perception of landslide severity, we performed a brief survey with a random sample of 40 people. Residents were shown three pictures with different levels of landslide severity, and were asked to specify which ones they considered landslides.

Additionally, we conducted open-ended interviews with the policymakers and written interviews with the scientific expert. In the interviews with employees from the District Commissioner's office including the Assistant District Magistrate, and a landslide expert from the Defense Terrain Research Laboratory, we investigated the current risk communication strategies in place and the potential opportunities for improvement. All interview materials can be found in the Methodology section of the Supplemental Materials on the WPI and IIT websites.

The information gathered from our groups of interviewees was organized in a database. We then analyzed the data through coding and created histograms to display the key findings from multiple sets of variables including village, age, and level of education. We established criteria to determine which warnings are sent to whom, and when, and developed an early warning system and bulk SMS messaging communication strategy to disseminate these warnings. An educational program involving an animated video and informative pamphlet were created to support the technical solution. Additionally, we conducted a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis to assess the effectiveness of our proposed strategies.

Results: Site Assessment and Interviews

In this section, we present our results according to our objectives.

Objective 1: Site assessment

Below, we present the results of our site assessment and interviews corresponding to our objectives. In total, 59 people were interviewed from the village regions of Katindhi, Dudar, Nela, and Khaliar. Additionally, policymakers from the District Commissioner's office and a scientist from the Geo Hazard Mitigation Division of the Defense Terrain Research Laboratory were interviewed.

When travelling to the different sites for interviews, photographs of the damage caused by landslides were taken. The photos provided us with an understanding of the level of severity of landslide events that have occurred in the Mandi District. For example, we visited the remnants of a landslide that occurred near the IIT-Mandi Kamand Campus. This landslide can be seen in Figure 5a. This landslide is larger in scale compared to others observed, such as the one shown in Figure 5b. From the site assessment, it was clear that landslides of varying severity occur in the area, but landslides such as the smaller one shown in Figure 5b are more common than the large one shown in Figure 5a.

Objective 2: Collaboration with our Stakeholders

Our open-ended interviews with the

Figure 5a.

Figure 5b.

Figure 5. The aftermath of landslides of varying severity observed during fieldwork

Assistant District Magistrate (ADM), the head of the relief department, and two representatives from the United Nations Development Program (UNDP) revealed important information regarding the current policies and strategies in place for landslide risk communication, as well as the progress that is currently being made to improve disaster risk communication in the Mandi district.

The interview with the Assistant District Magistrate (ADM) revealed that currently, there is no automatic prediction method for landslides in place at the district level. Rather, their department receives rainfall information from the Indian Meteorological Department and then the information is disseminated. A mass SMS message is sent to the functional departments that need to be informed, but this multi-step process does not reach the residents Additionally, when a landslide occurs, people call in the disaster to a 24-hour helpline in the police department where the operator then transfers the information regarding the disaster to the relevant party. Agencies such as the Indian Red Cross Society, and disaster management teams at the local level respond to the disaster following an established protocol that includes information regarding relief money to be allocated and responsibilities for responding to the disaster. The money is allocated according to the State Disaster Response Fund (SDRF) and the National Disaster Response Fund (NDRF) and varies according to the type of damage incurred. For example, 4.00 lakh may be paid to the family of a deceased person, if a person is killed by natural disaster, and Rs. 3,000 can be paid for the loss of a sheep, goat, or pig. The complete list of assistance available can be found on the Himachal Pradesh government website. The head of the relief department supported the information received from the ADM and also provided information about the hierarchy of communication in the case of a disaster. This hierarchy can be found in Figure 6.

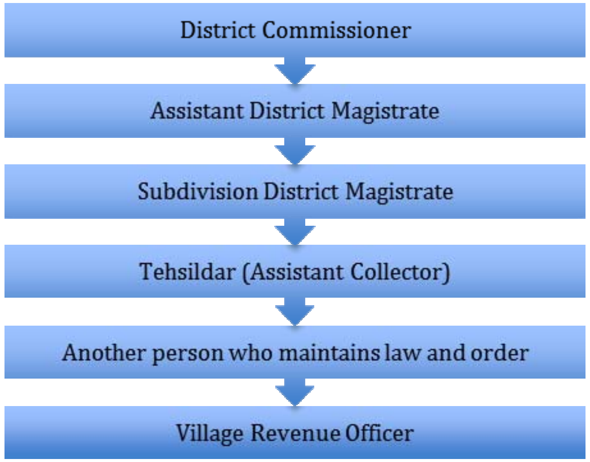

Figure 6. Hierarchy of communication in response to a disaster in the Mandi District

According to the interview with the representatives from the United Nations Development Program (UNDP), they are currently working as a liaison between all functional departments of the state government to help facilitate the communication for disaster management. They are focusing on community-based strategies, which include community feedback and outlining the responsibilities of each person. Additionally, they are working to train village leaders on how to respond to earthquakes, and are implementing informational sessions about earthquake readiness with local students.

The written interview with a scientist in the Geo Hazard Mitigation Division of the Defense Terrain Research Laboratory provided more information regarding the scientist's perspective on landslides and risk communication. According to the scientist, landslides are caused by prolonged rainfall, seismic zones, and anthropogenic activities and can cause effects such as traffic lams, injuries, fatalities, and economic and property losses. The scientist stresses the importance of educating people about the causes and consequences of landslides by providing simulations of the damage caused by landslides, as well as mitigation measures in order to advance the way people perceive landslide risk.

From our interviews with village residents, it was evident that many residents have developed a perception of landslide risk that does not correspond with the level of risk shown on the hazard map. Figure 7 shows the perception of landslide hazard risk of the interviewed residents in the Katindhi, Dudar, Nela, and Khaliar regions.

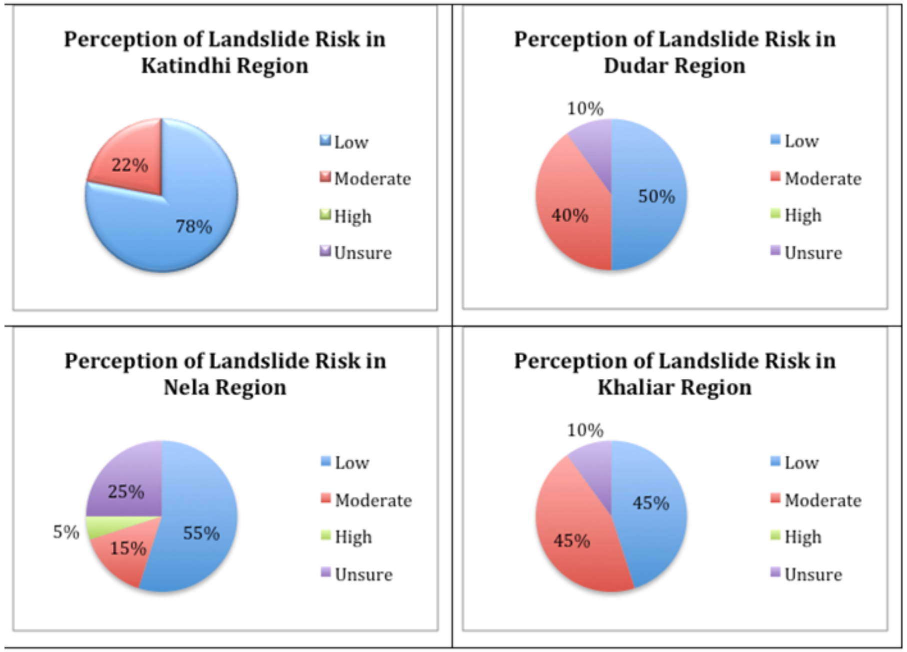

Figure 7. Residents' perception of landslide hazard in Katindhi region (Low Risk.), Dudar region (Moderate Risk), Nela region (High Risk), and Khaliar region (Very High Risk) based on interviews with the residents

Other questions from the interviews provide additional information regarding residents' opinions on various topics. These results were analyzed based on village, age, and education. Additional graphs detailing the complete results can be found in the Results section of the Supplemental Materials found on the WPI and IIT websites, but the key findings are highlighted here.

When asked why landslides occur, the highest percentage of interviewees believed that rain was a main cause, regardless of their village, age, or education level. Additionally, 37% of interviewees were unsure of what physical signs to look for in a landslide prone area that could indicate potential landslide occurrence. "Unsure" was a more common response than any mentioned by the policymakers and scientists.

Figure 8 shows additional responses, and illustrates how these responses vary between villages. The miscellaneous category encompasses the responses from both residents who were unsure, and those who did not provide an answer to the question.

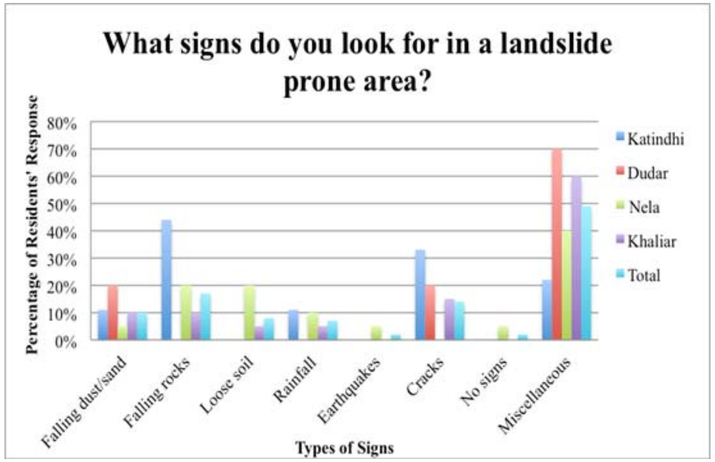

Figure 8. Residents' responses when asked what signs they look for in landslides prone areas

When asked about methods to reduce the occurrence of landslides, approximately 44% of residents believed that planting trees was an appropriate method, regardless of their village, age, or education level. Another common response was building retention walls, whereas some residents did not believe that any methods would reduce the possibility of landslides. Responses regarding the types of land use which trigger landslides varied by village, as seen in Figure 9. As in Figure 8, the miscellaneous category encompasses the responses of residents who were unsure, and those who did not provide an answer to the question.

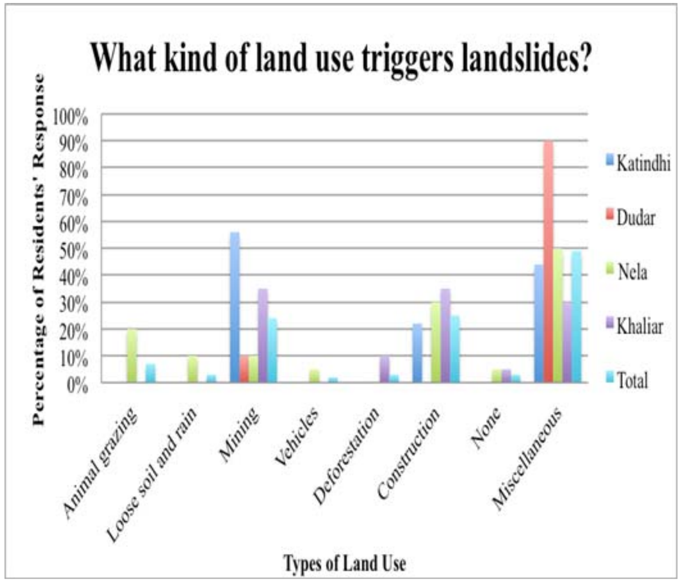

Figure 9. Residents' responses when asked what type of land use triggers landslides

Dudar was particularly less knowledgeable about the effects of land use, with most residents answering "unsure", or failing to answer the question at all, as depicted by the miscellaneous category. The residents were interviewed about the current policies in place to reduce this higher-risk land use, but more than 60% of the interviewees said they were unsure of the current policies in place. When asked if there was any funding available in the case of damage caused by a landslide, there was a fairly even divide between "yes" and "no", but some residents were unsure or did not answer the question. Additionally, more than 60% of people interviewed were unsure about current strategies in place to mitigate landslides. When asked what information they would like to receive in a landslide warning, many residents responded with "location", "severity", and "time" regardless of village, age, or education level.

Additionally, residents were shown three ways of presenting the same information: an info-graphic (metagraphic), a pie chart (graphic), and a table (tabular) and were asked which method of presentation was the easiest to understand. Whether or not their place of residence directly impacts their response is not clear, but the responses in Dudar differ more than the other villages. These results can be seen in Figure 10.

Figure 11 shows that when asked about their access to technology, most residents responded that they have access to a television, mobile phone, and the local newspaper, which many also mention as their common sources of obtaining news.

When asked about their preferred methods of landslide warning, residents responded that text message, loudspeaker announcement, and television were their preferred methods. Although these three methods were the most commonly mentioned, there were a wide variety of responses, depicted in Figure 12.

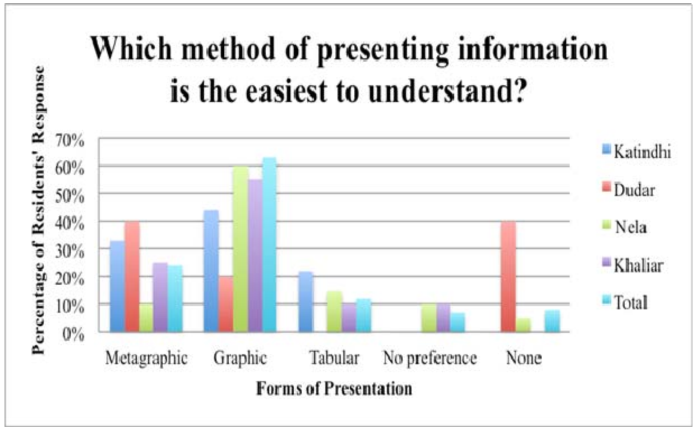

Figure 10. Residents' preference of the easiest method of presenting information

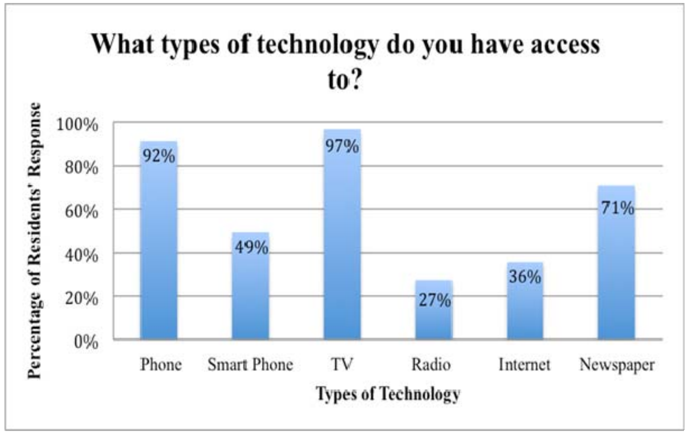

Figure 11. Residents' access to various types of technology

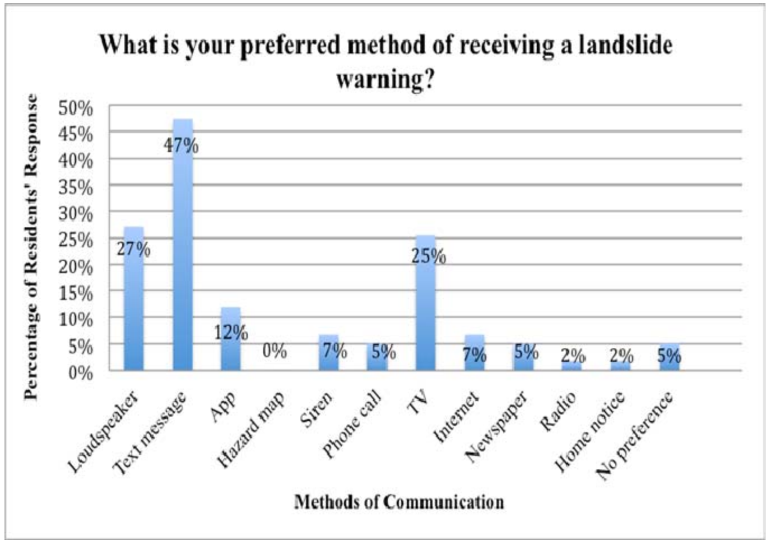

Figure 12. Residents' preferred methods of landslide warning

Residents were also asked if they would use a hazard map if one was provided for them. Fifty percent of people said they would use a hazard map, contrasting the 0% of people who mentioned the hazard maps as their preferred method of risk communication.

Discussion

Our interviews with the residents of Mandi District revealed important information regarding their perceptions of the level of hazard in their village and their general knowledge about landslides and the current policies and strategies in place, as well as their access to technology and preferred method of receiving a warning. The information obtained from these interviews was then utilized accordingly with the information obtained from the interviews with both the scientific expert and the employees in the District Commissioner's office in order to determine the most effective risk communication strategy to implement.

Perception of Landslide Hazard

The results obtained from asking the residents about their perceived level of landslide hazard in their village indicate that residents' perceptions consistently underestimate the level of risk shown by the Bhuvan landslide hazard map for those areas. The majority of residents interviewed in Nela believed that they were living in a low hazard zone, rather than the high hazard zone depicted by the hazard map. In Dudar, 50% of residents believed that the village is located in a low hazard zone, and 40% of residents believed that the village is located in a moderate hazard zone, corresponding with the map. In Khaliar, 90% of residents interviewed believed that the village is located in a low or medium hazard zone, whereas the hazard map categorizes the zone as very high hazard zone. Eighty percent of residents in Katindhi predicted the level of hazard in the village to be low. Although the hazard map does not include Katindi, we hypothesize that the level of hazard in the village is low because of its location on a mountaintop, away from potential debris fall. It is also important to note that significant percentages of residents were unsure about the level of landslide hazard in the area. This nuance could be attributed to local residents actually being unaware of the level of risk in the area, or being afraid to admit that they are living in an area with a higher level of risk. There is a clear discrepancy between residents' perception and the information presented by the hazard map, the policy tool currently used for landslide risk communication, according to the policy-makers and scientists. The hazard map may be inaccurate in places, but regardless, the discrepancy between what the map presents and what the residents perceive plays a crucial role in the success of a risk communication strategy because the stakeholders' perception of risk can determine how they will react to landslide events.

In order to determine if a difference in perception of the definition of landslides between the residents, policymakers and scientists plays a role in the gap in hazard perception, the residents' perception of severity was gauged with an additional survey involving photos of various landslides. From the survey, 63% of respondents said that they did not consider the smallest landslide shown to be a landslide. This response could provide a reason for why residents' perception does not align with the current hazard maps: the probability of all sizes of landslides may be considered when creating the hazard maps, not just the large-scale landslides that residents think of. Contrastingly, when the ADM was asked about the sizes of landslides, he responded that the definition of a landslide is very subjective and that there is no specific size involved in the definition. He stated that large landslides are reported if they cause a road blockage or damage to life or property, but other than that, the majority of landslides go unreported. This lack of consistent definition adds to the gap in communication.

An effective risk communication strategy will address the existing discrepancy in a two-pronged fashion: by raising landslide awareness through an educational program, and by providing a customizable warning based on location and severity of the landslide that will inform stakeholders of a landslide occurrence.

Guiding Principles for Education

Our findings suggest that there are gaps in understanding of knowledge of landslides and the policies in place between the residents, policymakers, and scientist. Many residents are aware of one or two causes of landslides, but are unaware of the human causes, some of the natural causes, the signs of a potential landslide, or the types of land use that can trigger landslides. The education strategy that we develop should address this gap in knowledge and aim to educate the residents in a way that promotes a community-centered approach rather than a top-down approach. Additionally, many residents mentioned that they would use a hazard map if one were provided for them in order to increase their awareness of the hazard level in locations they typically travel to, but that they would require education on how to use the map. Because the results do not show significant differences in knowledge level between villages, age groups, or education levels, for the majority of topics, one set of educational materials may be developed, instead of needing to alter the education material to each group.

Guiding Principles for Landslide Warning Systems

The results regarding the residents' access to technology demonstrate that a large majority of the 59 residents interviewed have access to a television and a mobile phone with text messaging capabilities. On the contrary, a much smaller percentage of interviewees use a radio. An effective landslide warning should incorporate technology such as the television or text message because it would accommodate a large majority of residents.

It is also crucial to consider the residents' preferred methods of receiving a landslide warning when creating a new strategy. Most residents are unaware of the hierarchy of communication, described in Figure 6, through which they should receive information, as explained by the head of the relief department. Therefore, our strategy should address the hierarchy of communication and include the village residents who are currently not involved in the communication pathway.

In order to bridge this gap, our developed landslide warning strategy must consider both the desires of the residents and what the policymakers and scientists believe is feasible. The most commonly preferred method of communication of the 59 interviewees was text message, followed by television, and then loudspeaker announcement. Although the majority of people prefer text messages, televisions, and loudspeaker announcements, each method has flaws that cannot be overlooked. Some interviewees mentioned that they do not have access to a mobile phone, or that they are illiterate and would only be able to understand a phone call and not a text message. Other residents mentioned that they would be frightened and confused by a loudspeaker announcement. Zero percent of residents preferred a hazard map as a communication method. The previously mentioned need for more education, combined with the lack of immediate notification provided by a hazard map are the most likely reasons that a hazard map is not a preferred method of communication. Text message and television, strategies that residents already have knowledge about and which can provide immediate notification in the case of a predicted or experienced landslide, are the preferred methods instead. When deciding which strategy to implement, we considered these technological preferences and limitations to determine the optimal solution. Additionally, the results obtained from questions regarding the information residents would like to receive in a landslide warning: location, time, and severity, combined with the response that a graphical method of presenting information will be useful in creating a technical solution.

Project Outcomes

From the analysis of our results, two main problems with the current conditions emerged: a lack of landslide education for residents, and a gap in risk communication between policy makers, scientists, and residents, particularly regarding the dissemination of landslide warnings and alerts. To address these shortcomings, we have formulated two recommendations, supported by SWOT analysis and cost-benefit analysis.

1. Develop an education plan to implement in conjunction with the United Nations Development Program (UNDP)'s Earthquake Education Program.
2. Implement a risk communication strategy utilizing mobile phones and SMS messaging to inform stakeholders of landslide occurrences.

Recommendations for an Education Plan

To increase the awareness of village residents about landslides, their causes, their prevention, and their mitigation, we recommend the development of an education plan, to be implemented in conjunction with the UNDP earthquake education program. Our results indicate that many village residents are unsure of the causes of landslides, and either do not believe that the possibility of landslides can be mitigated or are unsure of the ways to reduce this possibility. Additionally, many interviewees responded that they are unsure of the current communication strategies, and many residents answered that they were aware that they could receive governmental funding in the case of damage, but mentioned an inaccurate amount of assistance. This gap in knowledge needs to be addressed. Because there is currently a program being implemented by the UNDP for earthquakes, implementing a landslide education program in conjunction with the UNDP program has the potential to be successful. We recommend the creation of an informative video animation to be shown in the schools during the earthquake training sessions, and pamphlets as a take-away material for students to bring home to their families. In general, the video animation and pamphlets should address the key discrepancies and gaps in knowledge that have arisen in our interviews such as the causes and signs of landslides, and the policies and sources of funding available. We have created a sample animation and corresponding pamphlet, which can be found in the Project Outcomes section of the Supplemental Materials on the WPI and IIT websites. The video highlights rain as the leading cause of landslides and falling rocks as a key sign to look for, as well as phone numbers to contact in the case of an emergency and where viewers can learn more information about the assistance available to them. The pamphlet reiterates the same information, but also includes more specific details about the causes and signs of landslides, as well as the assistance available, with important funding information detailed in a chart. When combined with an improved technical solution, the education plan will help to improve risk communication in the district.

Recommendations for a Risk Communication Strategy

To bridge the existing communication gap between policymakers, scientists, and residents, we recommend the implementation of a risk communication strategy using mobile phone SMS messaging as part of an EWS to inform people of potential landslide occurrences, post landslide occurrences, and general information about landslides. The use of mobile phones can allow for a widespread warning with immediate notification. The text messages should be sent in Hindi, and should include information regarding the location, severity, and time of the event, as mentioned by residents in our interviews. Because text messaging is currently the strategy in place for communication at the administrative level, the principles are in place for efficient implementation at the local level as well.

Our proposed landslide risk SMS communication system is an early warning system that is based on rainfall data. It uses a user-friendly program that calculates the probability of landslide occurrence in specific regions. This is a semi-autonomous system in which the program allows the user to choose to send an educational message or a warning message based on the calculated probability. The probability is compared against a threshold calculated from a study on the National Highway-58 from Rishikesh to Mana in the Gartwal Himalaya (Experimental, 2015). This probability is shown to the user in a Graphical User Interface (GUI) so that the user may decide to send a warning, send an educational message, or to not send a message at all. The message is then sent to registered participants using Twilio Applications Program Interface (API). More information about Twilio, in-depth process flow of the communication system, system architecture, and code of the program can be found in the Project Outcomes section of the Supplemental Materials on the WPI and IIT websites.

This recommended communication strategy involves participant registration. In order to provide a platform for registration, we recommend the creation of a website. The website can also include access to the educational material and emergency contact information, and a method of communicating concerns and feedback about the communication strategy and educational material. In our prototype, the registration page and educational material are translated into Hindi, but in the implemented version, the entirety of the page should be in Hindi. When registering for the service, the receiver of the message will provide their telephone number and their location of residency, which are necessary for the landslide risk SMS communication system to send messages to the appropriate audience. The registration website is easy to access for those who use the Internet, but is uneasy for those without Internet access. An additional recommendation when implementing this strategy is for villages to hold registration sessions in which a computer is accessible, or information can be manually collected, and residents may register for the SMS service. To expand the benefits of the registration sessions, the educational animation may be shown, and educational pamphlets may be distributed.

Conclusion

Landslides are common in the mountainous Mandi District due to prolonged rainfall, seismic activity, and construction. Our study revealed two main findings: there is a lack of landslide education in the district, and there is deficient communication between the policymakers, scientists, and residents. A gap between residents' knowledge and the scientist's information exists, and oftentimes, the residents underestimate the level of landslide risk in their areas when compared to the hazard maps in place. Additionally, the residents are not currently included in the hierarchy of communication when disasters occur.

Based on interviews with the three stakeholder groups, we recommend the implementation of an educational program to increase landslide education and hazard awareness among residents. We also recommend the implementation of a landslide risk SMS communication system as an early warning system based on rainfall data to warn residents of potential landslide occurrences, inform them after a landslide has occurred, and provide them with additional general information.

To increase the scope of the recommendations, suggestions include conducting further research with residents to determine if the level of landslide hazard in the area they live affects their knowledge of landslides or perception of risk. If their place of residence is a determining factor in knowledge level, the educational materials could be altered accordingly.

We also recommend the implementation of a sensor-based system to acquire rainfall and soil data from regions to more accurately predict landslides, and to investigate alternate methods of registering for the SMS service in addition to the website. Additionally, we recommend transitioning to an Indian-based messaging service rather than an American-based one to ensure efficient communication. Our prototypes are easily adaptable initial steps to create an effective risk communication strategy in the Mandi District.

The full report and Supplemental Materials for this project can be found at:

http://www.wpi.edu/E-project-db/E-project-search/search, using key words from the project title.

Outcomes delivered after May 1 will appear on the IIT's ISTP page at:

http://www.iitmandi.ac.in/istp/projects.html

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Mitigating Noxious Gases Produced by Traditional Cooking Methods

Abstract

For generations, rural village residents in Himachal Pradesh have used traditional cook stoves, or "chulhas", which rely on firewood. Our project aimed to mitigate the gas production caused by this fuel and to alleviate the negative health effects. We designed an improved cook stove prototype with ventilation. Local women tested our prototype and provided feedback on the design, usability, and efficiency. Finally, we made a pamphlet of recommendations for the communities to mitigate the smoke and toxic gases within their homes.

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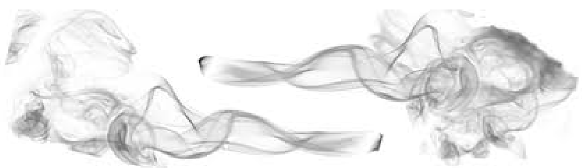
Cooking and Heating Practices in Northern India

In much of northern India, rural populations continue to use traditional fuel sources, primarily firewood. Though residents rely on this effective and easily accessible fuel, it releases toxic gases, such as carbon monoxide, which contribute to roughly 500,000 deaths per year in India alone (Lakshmi, Virdi, Thakur, et al., 2012). Research has found that exposure to these gases is also indirectly accountable for a range of diseases such as chronic bronchitis, pneumonia, and other acute respiratory and eye infections (Sood, 2012). In these studies, women and children are identified as the most at risk due to long-term exposure in their homes (Parikh, 2011). The levels of noxious gas has sparked a variety of proposed solutions including alternative power sources, stove tops, and heating methods. Despite substantial promise of the innovations, the targeted populations maintain their preference and reliance on traditional methods, thus continuing the exposure (Jeuland, Bhojvaid, Lewis, et al., 2015).

The District of Mandi, India, hosts a large number of rural villages whose residents use the traditional mud and brick cook stoves known as “chulhas” (see Figure 1) (Jeuland, Bhojvaid, Lewis, et al., 2015). Over the course of seven weeks in this region, we explored options for basic ventilation that could be an effective yet simple amendment to existing cook stoves. The goal was to manage the noxious gases produced through traditional cooking methods and to mitigate the effects on household residents. To meet this goal, we outlined the following objectives: (1) to understand the risks and limitations with current cooking and ventilation practices, (2) to design and build improved cook stove and ventilation prototypes, and (3) to gather test data and feedback to develop recommendations for the communities.

Figure 1. Traditional chulha (Baker, 2016)

These objectives established a deeper understanding of regional preferences in order to appropriately and effectively reduce noxious gases in parallel with raising awareness for safer practices in the communities.



Traditional Cooking and Ventilation Practices and their Impacts on Residential Health

Before performing our on-site fieldwork, we completed background research to identify the current methods of cooking and ventilation in the region, as well as to assess the related issues and any possible existing alternatives.

Community Resources

In order to better understand the scope of the project, it is important to recognize that stakeholders using traditional stoves are situated in small and often remote villages. While parts of the Mandi District are urban, the region has around 400 villages, sometimes consisting of just forty-three homes (see Figure 2) (Census of India, 2001).

Figure 2. Village in Mandi District (Codding, 2016)

Traditional building techniques in these communities rely on locally sourced materials including wood, slate, and cement. Typical structures feature wood framing, with cement walls, a slate roof, and a cement floor. The cooking areas are sometimes detached from the home but are constructed with similar material with the exception of mud-coated walls.

These structures, however, present certain limitations. There is no central heat in traditional Himachali buildings, and conventional electric appliances are rare. According to the Indian National Census of 2011, 58% of households in the state of Himachal Pradesh rely on firewood as fuel for heating and cooking (The Registrar General & Census Commissioner, 2011). Most households gather wood on a daily basis to fuel their chulhas (NIC Himachal Pradesh, 2015). However, as noted in numerous studies, “cooking with solid fuels (biomass such as wood, crop resides, dung, charcoal, and coal) over open fires or in simple stoves exposes household members to daily pollutant concentrations that lie between those of second-hand smoke and active smoking” (Pope et al. 2009, 2011; Smith and Peel 2010). The open stove surface does not include a chimney and kitchen windows are often placed too far away from the cooking area to act as natural ventilators.

> *“Cooking with wood over open fires or in simple stoves exposes household members to daily pollutant concentrations between those of second-hand smoke and active smoking.”*

Health Risks and Guidelines

In this scenario, where ventilation is lacking, the largest and most directly affected household members are women, as they are the ones most exposed to the noxious gases and smoke produced through traditional cooking practices. Across India, 34,000 women die annually from chronic obstructive pulmonary disease (COPD) as a result of long-term exposure to solid biomass fuel gases within their homes (Balakrishnan, Ramaswamy, Sambadam, et al, 2011). These gases contaminate the home and cause adverse health effects when released into a confined area with poor ventilation. Common conditions range from acute respiratory infections to eye infections to chronic health issues, such as cataracts, cardiovascular disease, chronic lung disease, pneumonia, tuberculosis, and problems with pregnancy (Epstein, Bates, Arora, et al, 2013; Parikh, 2011).

The science behind these practices is well-known. Any combustion reaction fueled by solid biomass fuels has the potential to release harmful chemicals or particles into the air. The primary noxious gases caused by biomass fuels are carbon monoxide and dioxide, nitrogen oxide, sulfur dioxide, and hydrocarbons (Lakshmi, Virdi, Thakur, et al, 2012). While carbon monoxide can be directly measured as a gas, the fine particles simultaneously produced by combustion are measured as levels of “particle pollution”, or PM. Specifically, inhalable particulate matter caused by fires are classified as $PM_{2.5}$, meaning they are 2.5 micrometers or less in diameter. These are the ones that contribute to respiratory problems and other hazardous health issues (see Figure 3) (EPA, 2015).

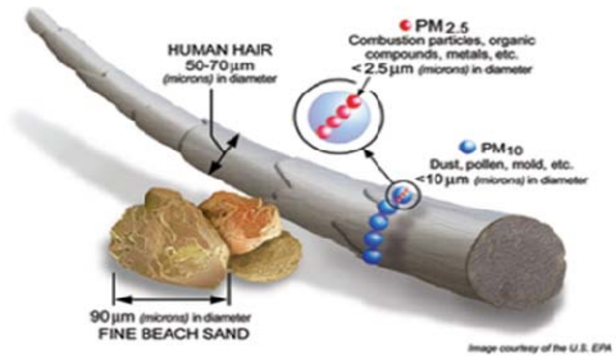


Figure 3: $PM_{2.5}$: Hazardous particle pollution. (EPA, 2015)

The United States Occupational Safety and Health Administration (OSHA), the United States Environmental Protection Agency (EPA), and the World Health Organization (WHO) have set standards for the most prominent particles and noxious gases produced through the combustion of solid biomass fuels, but they assume an eight-hour workday. In the typical poorly ventilated kitchen environment found within many village homes, these gases accumulate, exposing the residents for a majority of their time in the day. The policy guidelines fail to account for the inconsistency within a residential setting, including differing levels of gas production throughout the day, temperature, house settings, and the number of people exposed at one time. Various researchers have tried to establish a new set of international guidelines that take into account the difference in gas exposure levels in residential settings compared to strictly industrial settings (Clark, 2013; Jetter, 2012). However, the fact remains that the levels of noxious gases produced in the homes are dangerously high, with a large number of lasting adverse health effects.

Proposed Alternatives: Successes & Failures

In early 2015, in rural western Indian villages, alternative cook stoves (ACS) specifically designed with the aim to reduce noxious gas emissions were tested in homes and compared to the emissions from a tested traditional clay stove. The household air pollution (HAP) levels of each were monitored and compared to each other as well as to the WHO standards. The tested ACSs showed a reduction in noxious gas levels, but the traditional cook stoves produced an average $PM_{2.5}$ measurement roughly 36-fold higher than the WHO health recommendation of 25 ug/m^3 (Muralidharan, Sussan, Limaye, et al, 2015). The importance of this case study is twofold. First, the elevated levels of air pollution reinforce the need for improvement of current cooking and heating methods. Second, it conveys the need for a better standard of residential exposure levels. In the case of proposing alternative cooking and heating methods or ventilation system solutions, a baseline measurement of CO and/or $PM_{2.5}$ is essential. The significance of the value is not in its precision compared to the world standards, but in its use as a comparison when determining the success of an improvement method.

In 2012, Gunther Bensch and Jorg Peters presented a case study in which they recorded the overall response to the introduction of an improved cook stove (ICS) in a controlled trial in Senegal, Africa. When observing the impact of the implemented ICS, the authors examined the popularity of various types of cooking methods with both the experimental "treatment" group and the control group (see Table 1).

Table 1: Usage Percentage of Various Cooking Methods (Bensch & Peters, 2012)

	ICS Owners (Treatment)	ICS Non-owners (Control)
3 stones or Os	18.6 %	70.8 %
Traditional wood stove	7.1 %	23.6 %
ICS	70.9 %	-
LPG stove	3.4 %	5.6 %

Unlike other ICSs, Bensch and Peters' ICS continued to use traditional biomass fuel, but it was much more efficient in its fuel consumption. By continuing the use of traditional fuel, Bensch and Peters were able to extend the technology to a much wider base of recipients. In addition, the ICS consumed less biomass per meal cooked, and thus resulted in shorter meal preparation times. Bensch and Peters' ICS acted more as a "bridging technology", rather than a complete shift in the current culturally accepted cooking methods (Bensch & Peters, 2012). This approach can be paralleled to the villages in Himachal Pradesh, India, where this "bridging technology" may be more widely accepted.

Meanwhile, a recent case study in Kwale, Kenya focused on the effectiveness of different ventilation strategies on the reduction of biomass-related particle exposure in homes. Through some adjustments to a real-life kitchen replica, four scenarios were tested. The results presented that the use of any ventilation type decreased the concentration levels within the kitchens, with the chimney being most effective. The absence of a ventilation system did not show signs of lowered concentration levels. The study indicated that simple ventilation systems, especially chimneys, were an effective method in mitigating the gas level exposure in indoor areas.

Although a myriad of case studies have been done to improve traditional cooking methods, many models have only proposed modern alternatives like liquid petroleum gas (LPG) stoves, solar cookers, rocket stoves, and so forth. While these are suitable devices, they have not been widely adopted. Some villages even have LPG stoves, but nevertheless rely primarily on their traditional stove for cooking purposes. In sum, our review of literature revealed some positive case study recommendations, as well as several modern cooking advancements that have failed to take hold. With these precedents, our team worked to find a balance between current cooking practices and advanced cooking technology.

Methodology: Fieldwork and Prototype Development

The goal of our project was to manage the noxious gases produced through traditional cooking methods. Figure 4, below, summarizes our objectives.

3.1: Understand the risks and limitations with current cooking and ventilation practices

Our team identified participants from surrounding communities that were willing to partner with us so that we may understand local cooking and heating practices. We conducted a baseline assessment of the village communities through interviews with these participants by Hindi-speaking teammates. Responses were translated into English immediately following the interview. Additional documentation included photographing and filming the kitchen setup for the physical spaces and equipment used for cooking and heating. In addition, we made qualitative observations of the kitchen, which included noting if there was evidence of a smoke smell and blackened walls.

3.2: Design and build improved cook stove and ventilation prototypes

We designed a cook stove using traditional materials that included a simple ventilation system. We constructed an initial prototype inside an enclosed simulated kitchen structure on campus. Local materials were used to build the chulha in the traditional manner, and this included chopped pine needles, bricks, soil, fresh cow dung, iron rods, and a metal sheet. We learned the proper mixture of these materials as well as how to use it most effectively in building by a campus worker familiar with the art of building traditional stoves. As per convention, the chulha included three holes for cooking pots and an open area in the front for feeding firewood and cooking chapatis. We added a vent to our prototype that would not be found in common traditional cook stoves, for the purpose of connecting a pipe to act as a ventilation system. This first prototype required several days for drying. Meanwhile, we created a second, smaller-scale prototype with a slightly varied and improved design. While still made out of traditional conventional materials, this prototype added several innovations in order to further mitigate the smoke production and increase stove efficiency: a brick baseplate, an enclosed box shape, one side intake vent pipe for airflow, and one chimney pipe to channel smoke out of the house.

3.3: Gather test data and feedback to develop recommendations for the communities

After testing our improved campus prototype for its ability to hold a fire and boil water in a wok, we invited several primary household cookers to use our prototype. We asked them in semi-structured interviews to communicate feedback regarding its usability and efficiency. The field test generated results on both the functionality of the designed prototype and participant interest in using a non-traditional method. Empirical data included factors such as firewood efficiency, smoke containment,

1 Understanding Current Practices

- **Conduct baseline assessments to understand the risk and limitations of current cooking and ventilation practices.**

2 Prototype Design and Creation

- **Design and build improved cook stove and ventilation prototypes.**

3 Feedback Analysis and Recommended Development

- **Gather prototype test data and feedback to develop recommendations for the communities.**

Figure 4: Objectives for fieldwork and prototype development

Figure 5: Fieldwork Interviews

construction costs, and design limitations. User feedback was essential for determining perception of quality and usability. These criteria were used to refine the design and build recommendations for our stakeholder partners. The advantages, materials, visual construction instructions, and maintenance of the improved cook stove with ventilation were included in the final recommendation pamphlet. It was printed in both Hindi and English.

Results and Discussion

The results of our baseline assessment interviews and fieldwork confirmed our suspicions about traditional practices as they may promote undue exposure to noxious gases. The data are presented here by objective.

Objective 1: Understand the risks and limitations with current cooking and ventilation practices.

We visited six villages and engaged with a total of twenty-seven households. In these interviews, we found that 98% of households had either women or children cooking, and 2% of households had men cooking.

Figure 6 indicates the majority of respondents answered “no” when asked to report if there were any health issues that they believe

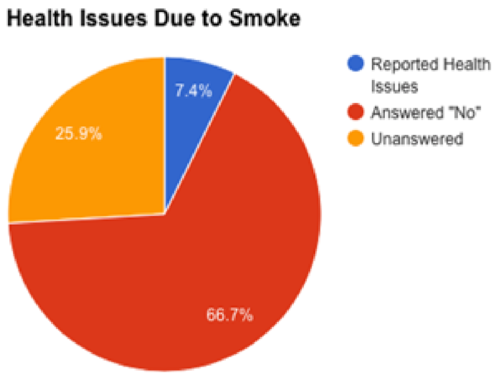


Figure 6: Responses from question asking about health issues due to smoke

were a direct result of long-term smoke exposure. However, 22% of respondents that stated “no” to this question went on to describe health issues they are experiencing in a question asking about issues they are having with their current cooking practice. In an effort to better understand these reported health issues, we began focusing on the cooking methods directly.

When cooking, the most common fuel used is wood with all households using it as their primary fuel source due to its accessibility. The upkeep of the wood stock within the homes was reported to be a prominent use of their time (see Figure 7). The reason for this wide range of data was not explained. Due to the amount of time these households spend collecting fire-

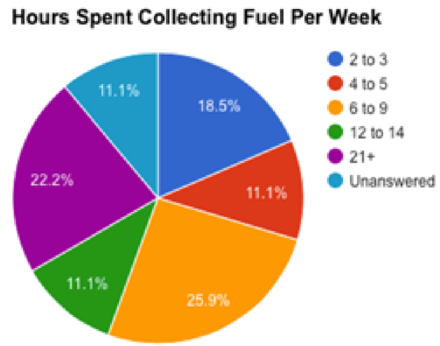


Figure 7: Reported hours spent gathering firewood per week

wood, village residents have expressed interest in a chulha that burns wood more efficiently. Currently, meals are taking long periods of time to prepare due to the inefficiency of the stove (see Figure 8). Along with the long hours spent cooking, women are

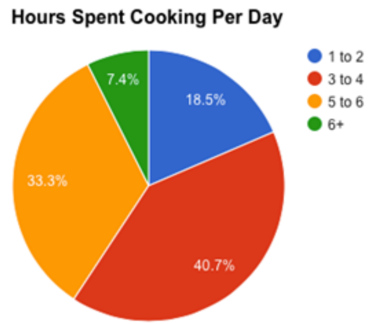


Figure 8: Total time spent cooking per day

being potentially exposed to these noxious gases for additional hours as they are boiling water, heating their homes, and maintaining their cooking area. Most of their additional hours spent in the kitchen are dedicated to maintenance as the excessive smoke production causes blackening to the cooking area and utensils (see Figure 9).

Figure 9: Blackened Cooking Area and Utensils in Runjha Village (Sharma, 2016)

Beyond the actual use of the current stove, we assessed the awareness within the communities of the need for an ICS or ventilation system. Twenty-six homes presented criticisms of their current methods. Many residents noted that the production of smoke was at an elevated level and some stated that their use of current traditional methods was causing health problems. Yet, the majority of the homes surveyed were unaware of proper ventilation techniques. These homes were using only small windows, which were blocked by various items and located far from their stoves, open doors for airflow, or simply tiny cracks in their roof as their main form of ventilation. However unaware of methods to alleviate the issue, all homes conveyed what improvements they wanted made to their current cooking method, which included a chulha that would produce less smoke while cooking and consume less wood.

Objective 2: Design and build improved cook stove and ventilation prototypes.

Our team formulated our chulha design by adapting it to be more efficient based on heat transfer theory. The first prototype had three cooking chambers, one central elbow pipe, and an open front for firewood (see Figure 10). It was built over the course of seven hours, including the collection of materials. This prototype was created in a simulated room with no proper windows and one door. The second prototype had one cooking chamber, one pipe situated in the top back corner and another on the side of the stove, and one closeable open front for firewood. It also took about seven hours to build, and around three hours were spent collecting materials. This second prototype was constructed in a shed with a metal-ridged roof.

Figure 10: Initial Prototype (Baker, 2016)

Our second prototype included several modifications from the traditional cook stove and a few imperative adjustments from the first prototype. The traditional stovetop has an open area for firewood as well as an open stovetop. There is no pipe or chimney, thus the smoke disperses everywhere and is not channeled in a certain direction. Modifications from the traditional cook stove include a box-shaped cook stove, two pipes (top and side), a baseplate, a closed stovetop, and a closeable front opening. The few adjustments made from the first prototype are the addition of a second pipe and the placement of the top pipe (see Figure 11).

Figure 11. Comparison of traditional stove in Nehri Village to second prototype. Arrows note the changes made, which include a box-shaped stove, a closeable front opening, a top and side pipe, a closed stovetop, and a baseplate. (Zhang, 2016)

Objective 3: Gather test data and feedback to develop recommendations for the communities.

During the first prototype testing, thin steel sheets covered two of the three chambers, and one chamber was covered with a small pot filled with water. Fire initially came out of the elbow pipe, but after a few minutes, smoke began flowing out instead. The water in the pot took about ten minutes to boil.

The second prototype was tested twice with a wok filled with water. The lip of the cooking chamber immediately blackened once smoke started producing. Smoke traveled out of the top back pipe as well as the front opening. No smoke travelled out of the side pipe. The side pipe stayed at normal temperature. Once the fire had gone out, smoke dissipated out of all open areas. During the second round of testing, our team blocked airflow to the side pipe. When the side pipe was covered, we observed that more smoke came out of the front opening than when it was left open (see Figure 12). We tested closing all openings except for the top back pipe when the fire had gone out. As a result, we observed thick smoke quickly escaping from the top pipe (see Figure 13).

Figure 12. Smoke leaving from front opening during testing; side pipe covered. (Zhang, 2016)

Figure 13. Smoke escaping from top back pipe during testing (Zhang, 2016)

Following our initial testing, we worked with a total of eight local village women who tested our prototype and provided observational feedback. Their initial thoughts were focused on their excitement of the traditional construction method. They felt the heat efficiency was better than their traditional stove as additional firewood was not needed. They commented on all the new structural changes as being added benefits for them. While there were many new aspects these women liked, they were critical of the aesthetics of the stove with emphasis on the front opening needing to be wider.

With less wood being consumed and smoke being directed up (see Figure 14), the women expressed they would use this stove over their current cook stove. In particular, they stated that the pipes were the key modification they wanted. Less smoke would create less blackening of the walls. Final remarks included advice on traditional construction.

Figure 14: Smoke leaving top pipe (Zhang, 2016)

Along with qualitative feedback, we recorded gas level readings for our prototype and compared them against readings taken in a village home located in Nehri Village (see Table 2).

Table 2: Comparative Gas Level Readings

Carbon Monoxide (ppm)	Traditional Stove		ICS Prototype		
	Top of Stove	Front of Stove	Top of Stove	Front of Stove	Pipe
Start of Fire	122	144	83	76	51
During Cooking	100	104	51	44	>1000
End of Fire	452	116	38	74	>1000
Control Air	58		47		

Gas level readings taken in Nehri were difficult as smoke quickly scattered as soon as it was produced. Women are exposed to a constant average of 173 ppm for the duration of cooking as well as the clean up process when using a traditional stove. However, women testing our prototype were exposed to an average of 61 ppm during the cooking and cleaning process. Little to no smoke was channeled out of the side pipe and front opening during cooking (see Figure 15).

Figure 15. Stove during Cooking (Zhang, 2016)

The readings taken from the above back pipe are not a factor in this average comparison as the smoke would travel directly out of the house through the roof.

Discussion

The data raised interesting points about the path forward, as well as some questions about appropriate technology design and engineering. Indian village women in the Himachal Pradesh region are reluctant to change their traditional cooking and heating practices. Regardless of all the new modern advancements being introduced, these women have still stuck with their traditional methods for decades. It begs the question, why would another new ICS design motivate them to switch out their traditional stove?

It was important to begin our project by understanding our stakeholders' perspective on traditional methods. From our findings, we see two key topics emerge that village women are passionate about and will, thus, determine the feasibility of our design being adopted within their homes: (1) fuel source and (2) stove construction. Wood is their primary source of fuel as it is easily accessible and available to them at no cost. Any other type of fuel is expensive and would require travelling long distances to obtain. Furthermore, traditional stove construction is a sacred practice that these women have stuck to for generations and have expressed their unwillingness to give up. To be compatible with their expectations, we created an ICS design that would continue those two practices. We simultaneously made several structural changes to increase efficiency and reduce smoke production during cooking. Change is incremental, and so it is important to recognize the hesitancy these women have when new ICS designs are proposed. Our team has found an appreciation for the availability and use of local materials as well as staying cost sensitive. While the stove is a new design, it is still identifiable as a "chulha". Based on our testing feedback, the women enjoyed the continual use of traditional mud and dung, and only had criticisms with small cosmetic aspects.

Although traditional practices can continue being respected, the most important question must be answered to completely determine the success of our ICS being implemented: what incentive do these women have to adopt our ICS? This project was grounded on the notion that a redesigned cook stove is necessary for women's health. While the science in the literature review supports this, our stakeholders have not identified it as a critical issue. Our findings around reported health effects were underreported and vague. Specifically, there was a low percentage of households that expressed having health issues related to long-term exposure. However, in another question focused on problems with their current cooking practice, many of the responses indicated their top issue was health-related. Based on this, we believe we may have either encountered an issue with the language barrier or our participants did not recognize certain symptoms as actual health issues. Our team has only collected self-reported medical data, and thus, answers to this question may not be accurate. These results raise the question of whether or not an improved health benefit can be seen as an incentive to them. However, it appears from the lack of reaction to prompts about health that this is not a good enough reason to change their current cooking method.

Moving forward to find a key incentive, we compared toxic gas level readings between the traditional stove and our ICS. The results show a significant change with about a 50% difference from the traditional stove readings. Though the gas level exposure has decreased substantially, this data has no bearing on local adoption. We predict this kind of awareness will develop more gradually over time as interestingly enough, we interviewed a doctor during our baseline assessment who expressed concerns about the harmful health effects associated with long-term smoke exposure. He built a rudimentary chimney to try to alleviate this issue, and some of these chimneys have been implemented in homes around the area.

Although his word-of-mouth approach to spread awareness about the harmful effects is commendable, it may take years for these women to actually value this information. For now, the two incentives that seem to resonate with the women are better fuel efficiency and a lesser amount of smoke produced during cooking. Women were persistent with their request for a cook stove that could burn less firewood and produce less smoke. The results from our ICS show the potential to meet these two attributes.

Our overall field test results were overwhelming positive. All of the women who tested our prototype shared their enthusiasm to use our ICS and even voiced they would be willing to pay for this ICS to be implemented in their homes. They were extremely impressed with our design as it was able to incorporate a solution to their two top issues while still maintaining traditional function and form.

Project Outcomes

Prototype Recommendations

Due to time restraints, we recommend testing our prototype in a village home for a period of several weeks. This will provide a proof of concept prototype that will gauge if it can be adopted over time. The prototype would need to be built to exact local specifications with a chimney fitted to the roof.

Other recommendations include adding an eighth-portion of cement to the cow dung and dirt mixture to prevent cracks from forming during the drying period. Cement will also reduce the maintenance frequency as it will not crack or degrade as quickly as the dirt and cow dung mixture will. Furthermore, we recommend adding a damper to the side pipe to more easily open and close the side pipe when needed. The side pipe must remain horizontal without a bend or an "L" shape in order to properly function as a chimney damper. A bend would distract the pulling of air in and thus damage the back pipe's performance.

When constructing the chimney, we recommend using a flat metal sheet as the means of attachment to the roof. In the case of the typical household slate roofing, one slate would be replaced with this metal sheet. To secure the pipe, a hole should be cut in the sheet that is to the exact dimensions of the pipe. It is important to run the pipe through the hole and weld it in place so that it fits tightly in the metal sheet. Drill holes through the pipe above the metal sheet to allow for smoke to escape and cover the top of the pipe by welding an additional piece of metal sheet to it and adding a metal "cap" (see Figure 16). This top cover prevents rain from entering the chimney and protects the stove from weather. The pipe should be installed in an area that is away from flammable items as the chimney become extremely hot during cooking.

Figure 16.: Chimney "Cap" (Codding, 2016)

When cooking, our team suggests opening the side pipe to promote airflow in and thus reduce the amount of smoke leaving from the front opening. After cooking, we recommend closing the front opening with a mud-coated thin steel sheet and covering the side pipe. By doing this, the smoke will be directed up through the top pipe and out of the house.

Our design calls for yearly maintenance in order to prevent potential house fires. The chimney pipe should be removed from both the side and back top once a year. It is recommended that both pipes be properly swept out with a steel brush to clear out any built-up soot. After, the pipes can be put back into the stove structure and mud can be reapplied.

Construction Pamphlet

In order for future residents of the Mandi region to be able to build their own cook stove with the design of our ICS prototype, we have created an instructional pamphlet. This pamphlet contains a list of the necessary materials, step-by-step instructions with ample visual aids, maintenance information, and a gas exposure health fact. The pamphlet, which can be found in the Supplementary Materials on the WPI IQP site, was written in both an English and Hindi version.

Conclusion

Ultimately, while our findings and recommendations appear to take a step back from newly proposed cook stove innovations, we learned that modern stove advancements will not be adopted without incremental steps that can bridge the two extremes. Thus, our team stresses the importance of continuing traditional construction methods and fuel use for our ICS design. Incorporating these two key aspects into future ICS designs is significant for the gradual progression of improving traditional cooking practices. These themes were the primary passions of the village residents, as found by our initial interviews, and remained as two of the most praised aspects of our ICS prototype during stakeholder testing. While the goals of this ICS is to reduce smoke production and increase heat efficiency for the immediate benefits of less maintenance, fuel, and cook times, these are in actuality the perfect ways to decrease exposure to the produced toxic gases, and therefore improve overall health of the exposed families in the Himachal Pradesh region.

Acknowledgements

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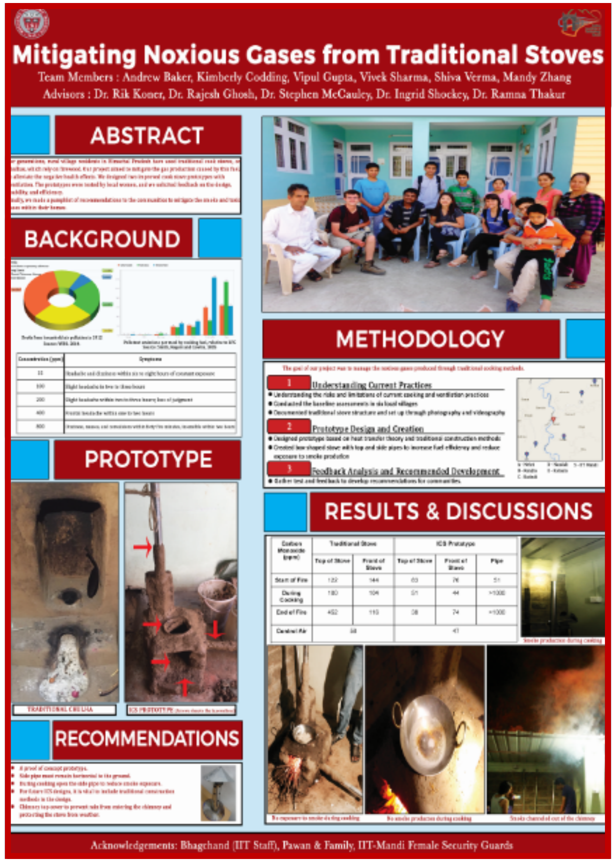
The full report and supplemental materials for this project (raw data, relevant case studies, the instruction pamphlet, and additional resources) can be found using key words from our project title at http://www.wpi.edu/E-project-db/E-project-search/search and further information can be found at the IIT's ISTP page: http://www.iitmandi.ac.in/istp/projects.html



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Improving Healthcare Coordination in the Mandi District

Abstract

Rural healthcare workers in the Mandi District face unique challenges in providing quality care due to mountainous terrain and lack of supplies. This project evaluated the existing system of communication between health centers and identified areas in which the system could be improved to mitigate the effects of these challenges. We recommended a new system for medical stock requests and deliveries which could decrease delays by up to fifteen days and ultimately improve the quality of care for patients.

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An Interactive Qualifying Project/Interdisciplinary Sociotechnical Project submitted to: WPI

Enhancing Communication in the Mandi District Health System

Rural communities around the world characteristically struggle to administer healthcare that matches the standards set in urbanized areas due to a lack of resources, in terms of both personnel and procedural capabilities. These challenges tend to be explained by limited funding, geographic inaccessibility, and the complexity of disease patterns (see Figure 1). The Mandi District in Himachal Pradesh of Northern India experiences all of the challenges of rural healthcare, exacerbated by the mountainous terrain and uneven connectivity in the state.

The goal of our project was to support the development of new communication systems for facilitating coordination between health centers in the Katuala block. In this way, patient records and medical supply inventories could be better maintained and better transferred between different tiers of the public healthcare system in the Mandi District. This would cut down on wait times and the need to repeat procedures, as well as optimizing the availability of medical stock. To achieve our goal, we completed three objectives. First, we examined stakeholder needs and technical capacity, including critical gaps in the existing network. This helped us understand the baseline communication system that each center had. Second, we identified and ranked possible communication solutions in terms of cost, feasibility, and effectiveness. Lastly, we developed and tested a proof of concept software solution to be implemented in the healthcare system, and generated recommendations for further improvement of communication in healthcare.

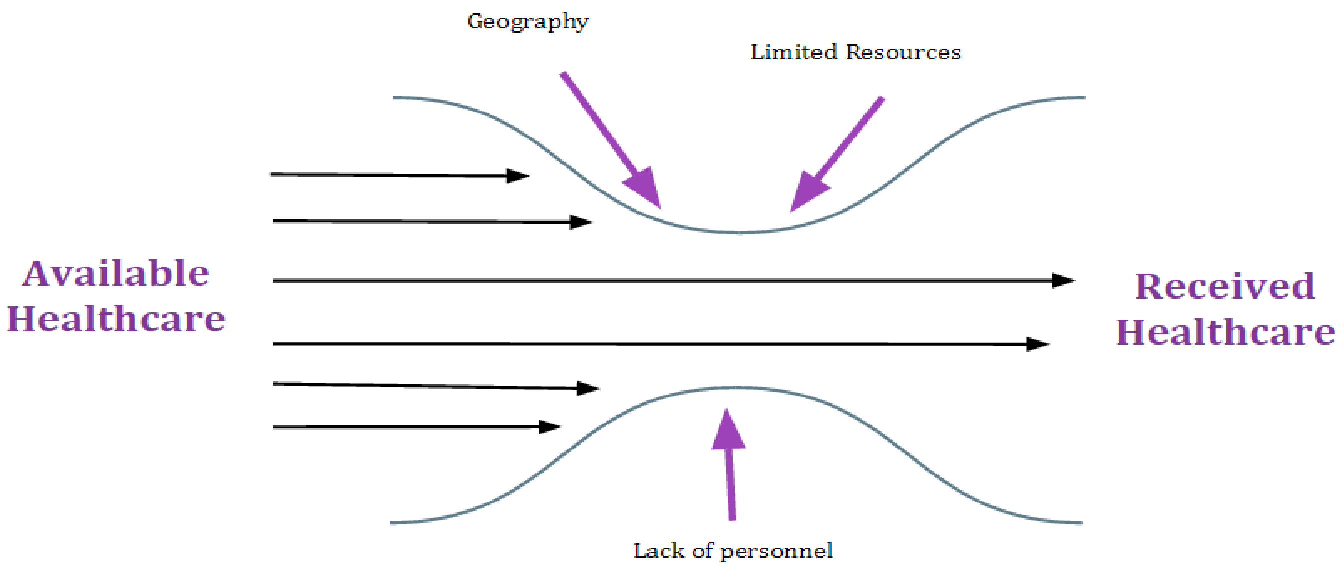


Figure 1. Healthcare bottlenecks in Mandi District (adapted from Gauba, et al., 2015).

Challenges in Rural Healthcare

There are multiple documented discrepancies between urban and rural areas with regards to healthcare administration. In 2015, a team of students from the Indian Institute of Technology in Mandi and Worcester Polytechnic Institute assessed the primary obstacles to healthcare in the Mandi District (Gauba et al., 2015). The team assessed multiple healthcare facilities, including the Zonal Hospital Mandi and an extensive network containing multiple sub-centers within the medical block of Kataula, which was ultimately mapped.

By developing and implementing a Rural Healthcare Assessment Model, the Gauba et al. project team identified three critical bottlenecks to healthcare administration in the region. The first bottleneck was inhibited physical access to facilities due to challenging mountainous terrain coupled with poor road quality, an example of which can be seen in Figure 2. The second bottleneck was related to limited supplies and medication due to sporadic delivery schedules and poor access, leading to high delivery costs. The third bottleneck was limited access to welltrained specialists, especially at the smaller, understaffed sub-centers. These bottlenecks could be overcome through increased coordination, such as improved communication, organization, and healthcare portability solutions.

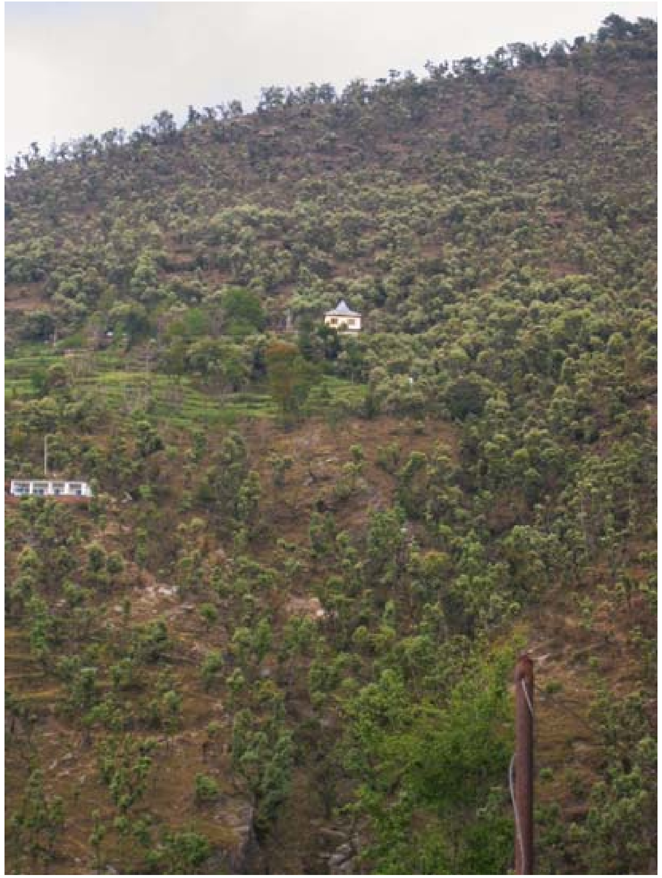


Figure 2. Picture showing the remote location of the Balmand sub-center (Gauba, et al., 2015).

Partially due to bottlenecks that restrict rural healthcare, serious discrepancies exist in the quality of healthcare between rural and urban areas. For example, in the case of road accidents, the higher death rate in rural areas such as Himachal is a function of "lack of first aid, delays in transfer of patients, longer time interval between injury and reaching a definitive hospital, absence of triage, [and a] lack of facilities in hospitals" (Gururaj, 2008). Similarly, 85% of preventable deaths due to diseases such as diarrhea and pneumonia occur in rural areas, suggesting that "the majority of care for these children, if any, was provided locally and likely by those lacking comprehensive health training" (Morris et al., 2011). These findings highlight the need for more efficient communication systems which could better manage inventories of antibiotics and other supplies, or could facilitate the transfer of patients between hospitals.

There are a variety of key stakeholders invested in the implementation of an improved health coordination system within the Kamand and Mandi region. The most invested are healthcare providers, including officials such as the Chief of Medicine, doctors, and clinic staff. Healthcare staff face challenges maintaining inventories of supplies, storing patients' histories, and transferring patient information between healthcare tiers. Patients are also important stakeholders, as coordination can have direct impacts on their quality of care. There are often long waits at health centers because staff must collect the same information at each visit due to lack of communication, which leads to wasted time and possible endangerment of patient health.

A 2008 case study in rural South Africa found that rural clinics often struggle to maintain, transfer, and use patient information (Garrib et. al., 2008). The researchers analyzed quality of the data entered into a newly implemented District Health Information System in ten different healthcare facilities. The results indicated a high perceived work burden of data collection and entering. There was frequently missing data and little explanations for abnormal data values, along with limited use of the data. If a system is not intuitive, its users will not use the program features they do not know or care to use. These findings helped us design a system that is not only user friendly, but useful to different healthcare administration levels in rural areas of Himachal Pradesh.

A 2011 case study in Himachal Pradesh compared and contrasted two different methods of developing a Health Information System, or HIS (Oygard & Valland, 2011). Open source software (OSS) development involves multiple companies and individuals collaborating to build constantly evolving free software, allowing developers to modify the code of existing, freely available infrastructure to aid implementation within specific settings. Its main limitation is that, in some cases, a HIS may have to be designed from scratch to adapt to an especially unique setting (Oygard & Valland, 2011). The second method outlined is known as Agile Software Development, which places high emphasis upon lightweight development methods, flexibility and rapid response to changing environments. Personal communication and constant contact with stakeholders is also a major part of Agile philosophy. These characteristics are highly desirable with regards to HIS development, as the needs of medical facilities change constantly (Oygard & Valland, 2011). The comparative information outlined in this case study helped guide our choice of software development methodology in the later stages of our project.

Methodology: Understanding Existing Infrastructure

In order to support the development of a new software for facilitating communication between healthcare providers, we achieved the three objectives shown in Table 1.

We started our interviews with informal visits to the clinic on the IIT campus and the Zonal Hospital Mandi to gather basic contact information for the health centers, as well as general information about the health system and need for improved communication. Post-interview translation of voice recordings into English transcripts was first used, but then simultaneous translation was adopted to include all team members in the interview. We then conducted interviews with doctors and staff at health centers from four tiers (sub-centers, primary health centers, community health centers, and zonal hospitals) to assess their technical capacities, perceptions of communication problems, and thoughts on possible solutions. Our primary focus was on the Kataula medical block (shown in Figure 3) which includes the Zonal Hospital Mandi, the Kataula Community Health Center, and seven sub-centers located in the villages of Tandu, Taryambli, Riyagri, Kamand, Tihri, Namlay, and Balmand. We also conducted interviews at the Padhar Community Health Center and the Phali Primary Health Center to assess how representative communication within the Kataula block is of other medical blocks in the Mandi District. Together, these eleven chosen health centers gave us a good representation of the different interactions between the four tiers.

Table 1. Objectives and associated strategies.

Objectives	Methods
Determine stakeholder needs and technical capacity, including critical gaps in the existing network	• Site assessment • Semi-standardized interviews
Identify and rank communication solutions in terms of cost, feasibility and effectiveness	• Feasibility analysis • Solution selection
Develop and test a proof of concept for a communication solution in the healthcare system	• Software development • Feedback collection

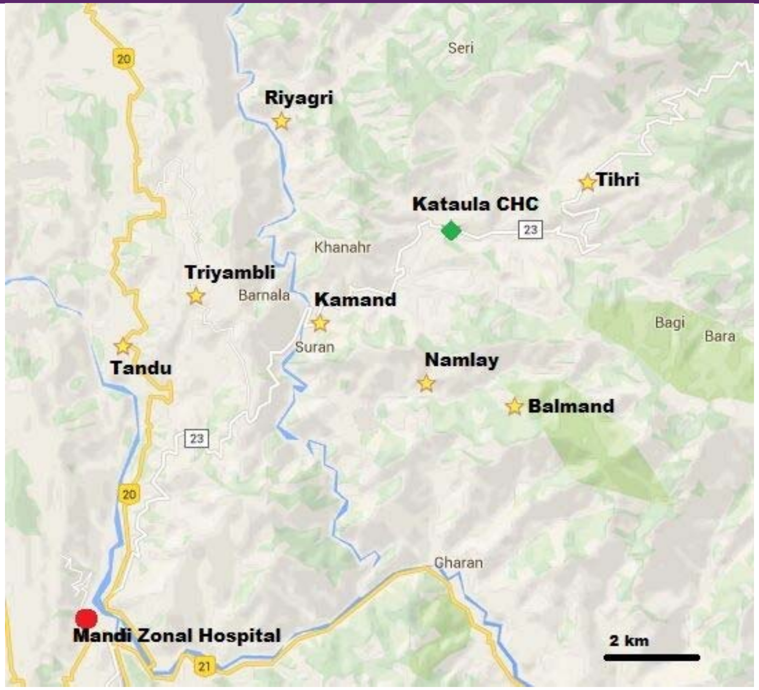


Figure 3. Map showing healthcare infrastructure of the Katuala block in the Mandi District.

A picture of our team conducting interviews can be seen in Figure 4.

The results of the interviews were used to determine sub-center technical capacity, allowing us to conduct a feasibility analysis of possible communications systems based on what the existing infrastructure could support. Aspects of the existing systems were also analyzed in order to determine the area with the greatest need for improvement. Using this information, an appropriate communication system was selected. System requirements and design, as well as all necessary materials, were compiled in a single document to facilitate the development process. After development of a prototype, the system was introduced to the District Program Officer at the Zonal Hospital Mandi to obtain feedback about

Figure 4. Conducting interviews in Neri.

the system and suggestions for improvements. Final recommendations were compiled for the development of future government programs related to healthcare communication.

Results

Completing interviews at the eleven health center locations helped our team determine what needs and capacities the stakeholders have. We also learned about the flow of information and supplies between the four healthcare tiers.

Healthcare Infrastructure in the Mandi District

Sub-centers are the smallest unit of the healthcare hierarchy and the first point of contact with the system for most of the community, followed by larger primary and community health centers, all of which are overseen by the main zonal hospital. Each of the seven sub-centers within the Kataula medical block serves a population ranging from 800 to over 3,000 residents. They are each staffed by a male and a female health worker. In the Mandi District as a whole, there are 311 sub-centers, served by 61 primary health centers, 13 community health centers, and 6 hospitals.

Patient Care in Sub-Centers

Health centers fall under two main categories, preventative and curative. Through interviewing health workers in the Mandi District, our team discovered that basic sub-centers only provide preventative care, with limited first aid capabilities. As stated by the District Programs Officer, Mrs. Anuradha Sharma, “The sub-centers are basically focused on preventative… they look after programs like immunization, family planning, tuberculosis and malaria eradication, and other vector borne diseases.” For curative care, patients must go to the higher level health centers like the Kataula Community Health Center (CHC) and the Zonal Hospital Mandi (ZH), shown in Figure 5.

Figure 5. The Zonal Hospital Mandi.

Out of the seven sub-centers where interviews were conducted, none of the health workers at any location said that referral slips were used. On average, only one patient per month is referred to a higher health center. This referral process is either done through calling the higher level center to warn that a patient is coming or not communicated at all. Most patients understand that the sub-centers are unable to provide curative care and travel to a larger health center without first stopping at the lowest level.

Medical Stock Information

Sub-centers maintain stocks of simple medicines and supplies to attend to preventative needs and minor ailments. These supplies include mild painkillers, vitamins, cold medications, TB immunizations, and first aid supplies such as wound cleaners and dressing. The sub-centers are supplied with medical stock from higher ranked medical centers, flowing from the ZH to the CHC before continuing to the sub-centers as shown in Figure 6 below.

Six out of the seven sub-centers interviewed reported that they receive stock from the Kataula CHC, the exception being Tandu, where stock is received directly from the ZH due to its close proximity (see Figure 6). The process of restocking begins in a monthly meeting in which workers from all seven sub-centers travel to their higher-tier center and request necessary stock as recorded in a handwritten stock register. This requirement of a scheduled in-person meeting sometimes causes delays of up to 15 days between an apparent need in a sub-center and the notification of a higher-tier center.

All sub-centers also reported frequent delays in restocking between 5 and 14 days after this monthly meeting. However, none of the sub-centers reported that stock shortages happened because of delays from the CHC; one sub-center worked indicated the issue was with back-end supply, saying that "...[the CHCs] have a storage problem, so they try to get the stock out as soon as they can…[but] it could happen that there is a delay from the ZH to the CHC." This was confirmed by a health worker staffing a different sub-center, who reported that "...many times supply does not come. But if the ZH has stock, then we are supplied immediately." Interviews at the CHC Kataula revealed that they have a vehicle which is used to pick up supplies from the ZH. Another sub-center worker indicated that delays could be reduced if stock was supplied directly from the ZH rather than having the CHC as a middleman, because occasionally she cannot attend the monthly restocking meeting to avoid the sub-center being unstaffed.

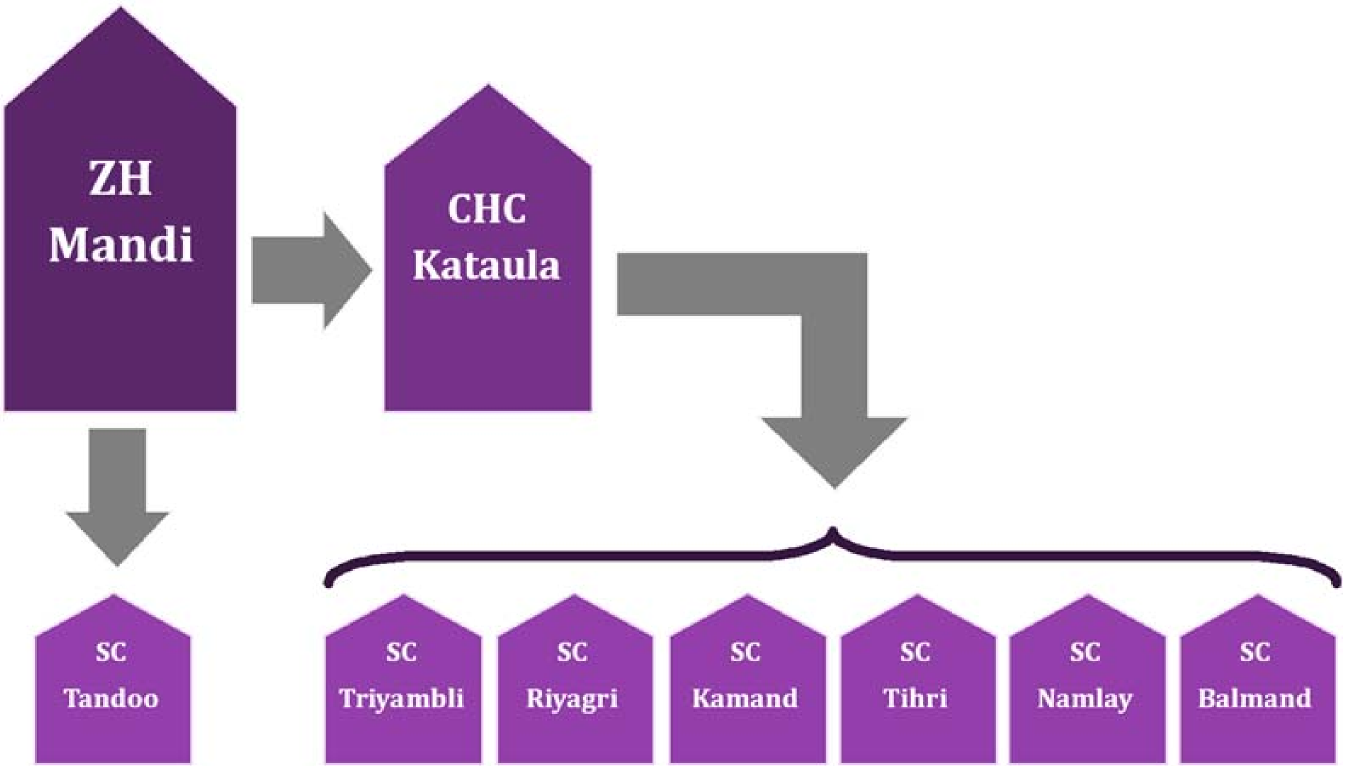


Figure 6. Coordination chart representing the flow of medical stock in the Kataula block.

Financial & Technical Capacity

Each sub-center has a bank account and is supplied with an annual maintenance grant of Rs 10,000 every two years. This grant can be utilized for general sub-center maintenance such as purchasing chairs or equipment. Medical stock is paid for by the Zonal Hospital in most cases. If there is an urgent need and stock has yet to be resupplied, the sub-centers also receive an untied fund to buy medical supplies from government authorized stores.

The technical capacities of the sub-centers were recorded and are shown in Figure 7. Each sub-center health worker is supplied by the government with a basic Nokia C1-01 cell phone, capable of talk and text. Each month, each health worker is supplied with a Rs 50 recharge for this mobile device. One of the health workers, however, said that he uses his own money to recharge this phone because it is a tedious process to obtain the recharge money and Rs 50 is not enough to make it through each month. All seven of the sub-centers have cellular service for voice calling and text, but the most remote sub-centers sometimes have difficulty connecting well. Because the sub-centers do not have reliable access to the internet, they are not supplied with smartphones, tablets, or computers. Even if internet access and computers were present, the sub-centers often have power outages of 1-5 hours per week; these outages being worse during the summer months and very frequent during storms.

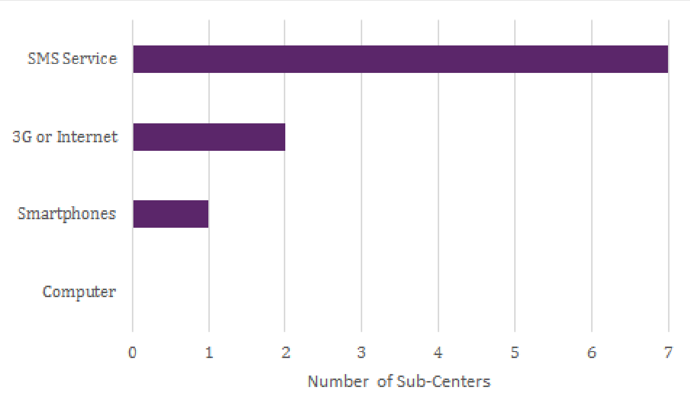


Figure 7. Number of sub-centers with various kinds of technical capacity.

Discussion

The results of the interviews conducted revealed trends in health worker perceptions and connectivity issues of the current system.

Health Worker Perceptions

Sub-center health workers indicated that a system to forward patient records to higher tiered health centers would not be necessary because patients usually know they should go directly to the Kataula CHC or Mandi Zonal Hospital if they have an ailment that is serious enough to require testing. Although most sub-center staff showed no appreciable need for a patient record-keeping system, they did indicate more of an issue with regards to medical stock. Currently, a lack of electronic communication can cause delays in notification of stock exhaustion, preventing sub-centers from providing adequate care. Six of the seven sub-centers interviewed believed that improvements to the restocking system would be a positive change. From this trend, we focused our project on increasing communication and coordination surrounding medical stock between tiers.

Connectivity and Technology

Due to major connectivity issues and lacking technology, the range of solutions that can be implemented are severely limited. If better technical infrastructure was available to sub-centers, the feasibility of self-entry of data online would be higher. However, due to poor cellular data connectivity, an online data system might still fail. From utilizing our own phones as a measurement, only two of the seven sub-centers had a cellular network strong enough to support 3G or higher data browsing. The overall trend seen in the sub-centers is that implementing smartphones, tablets, or computers is not feasible, although government involvement in the coming years may increase their capacity to do so.

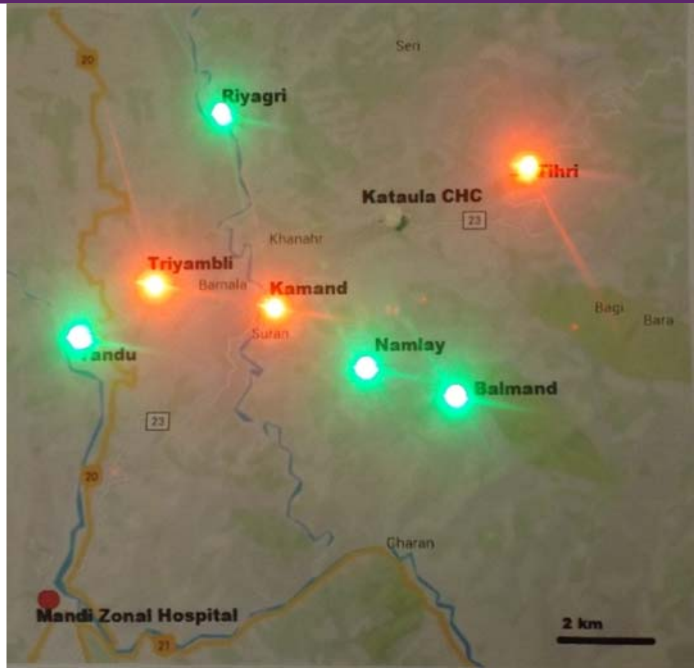
Project Outcomes

Our findings indicated that insufficiencies in the communication system between health centers create a burden for health workers, ultimately detracting from the quality of patient care. To address these issues, we developed a number of recommendations for the government and the District Program Officer that will streamline the process of restocking medical supplies. These recommendations are based around the adoption of a system we developed to reduce delays in notifying the Zonal Hospital of stock needs, coupled with future improvements to the system.

Visual Stock Indicator System

To decrease the delay in restocking medical supplies to sub-centers, we propose the adoption of a Visual Stock Indicator System (VSIS). Such a system would allow workers at sub-centers to convey their need for medical supplies via a text message sent to a server at the Zonal Hospital Mandi, which operates effectively on the existing telecommunications network with the workers' government-provided phones. These messages would be received by the system and translated into LED indications on a map located at the Zonal Hospital and CHCs. In the initial prototype, green is a normal indication. Red indicates an unanswered stock shortage and request, and yellow indicates that the order is available at the CHC. When the status of a sub-center is changed to yellow, an automated SMS will be sent to update the sub-center worker. Specific details about the stock request would be visible on a website based interface, which would be open on the pharmacist's computer. Workers at the Zonal Hospital would then be able to purchase medical supplies if necessary and notify the sub-centers directly when their stock is available for pick-up. A working prototype of the VSIS system can be seen in Figure 8.

The implementation of a VSIS would confer several benefits to the medical stock resupply system. Primarily, it would eliminate delays caused by the current process of notifying that stock is running out, as sub-centers would be able to immediately communicate their need instead of waiting for a monthly meeting to do so. It would also allow sub-centers to contact the Zonal Hospital directly, removing the delay caused by communication from the CHC to the Zonal Hospital. These two improvements could prevent delays of 15 days between the realization of the need for more supplies and the notification of the Zonal Hospital, and could eliminate the need for a sub-center worker to spend a day travelling to report stock needs. The benefits of this system would come at no additional cost to sub-centers, as they already have government-provided cell phones. The cost of initial implementation at the Zonal Hospital and Kataula CHC would be roughly Rs 3843 each (about $57 - see Table 2). Costs to maintain the system once installed would be minimal. The physical component that would be most likely to fail are



Medical Stock Data

Health Center wise stock status is shown below:

Health Center	Stock Availability	Required stock	Stock Request time
Kamand	Stock Required	paracetamol	Sun Apr 24 2016
Triyambli	Stock Required	acetaminophen	Sun Apr 24 2016
Tihri	Stock Required	cetirizine	Sun Apr 24 2016
Navlay	Stock OK	NA	Sat Apr 23 2016
Balmand	Stock OK	NA	Sat Apr 23 2016

Figure 8. Photograph of VSIS prototype showing stock outages at Tihri, Triyambli, and Kamand sub-centers, with relevant website output.

the LED indicators and wires, which would not be expensive to replace if they failed.

We evaluated the possibility of more simplistic and direct means of communicating stock needs, such as direct texting or phone calls to personnel at the ZH. The light-board would serve as a more persistent reminder to ZH personnel, as the LED would remain illuminated until action is taken, whereas simple texting is a one-time notification and easy to forget. The system also presents the information in a more standardized and organized fashion. Given the doubling of 3G usage in India from 2014 to 2015 (Nokia, 2015), it is likely that 3G cellular data will soon become available at sub-centers not presently covered. This would allow for expansion of the light-board system to a digitized smartphone or tablet system. Our SMS-based system would therefore serve as an initial phase in improving stock communication, allowing the health centers and workers to develop organizational practices based on direct messaging. A mobile app format would ultimately serve as a

Table 2. Estimated total cost of implementation for a VSIS.

Part Description	Estimated Cost (Rs)
2 AC/DC Power Adapters	340
30 Wires	90
8 Multicolored LED Bulbs	48
Map and Box	65
GSM Module	800
Raspberry Pi	2500
Estimated Total	**3843**

more user-friendly, long-term solution, capable of providing a greater degree of two-way communication once there is sufficient cellular infrastructure to support it. Once consistent 3G coverage is available, it would be a simple transition to have a 3G based mobile app send stock requests to the already implemented hardware.

Additional Policy Recommendations

In addition to the implementation of VSIS, we recommend adaptations to the current system of stock flow in the Kataula block. Upon implementation of VSIS, stock requests should go directly to the ZH rather than to the CHC. This will ensure that requests arrive at the ZH as early as possible, allowing them to order back stock in a timely manner if it is not available and reducing common delays associated with the ZH lacking supplies.

Figure 9. Receiving feedback on the VSIS at the Kammand sub-center.

Once the ZH orders back-stock (as required) and sets aside the order, the CHC should send a vehicle to pick up the stock, which will then be appropriately distributed. If a sub-center urgently needs supplies, the CHC should deliver stock directly to the sub-center; otherwise, the orders can be set aside to be picked up by the sub-center health worker at their monthly meetings. It is possible that a stock-out light illuminated for a long period of time will lose relevance to the pharmacist in charge. In order to alleviate the risk of overlooked requests, future features of the system could include an automated series of text reminders to the pharmacist after two weeks.

Conclusion

Our interviews with health care workers in the Mandi District revealed several areas of possible improvement in the communication systems between health centers that are currently in place. These shortcomings include the need for manual transmission of statistical data from sub-centers to higher tiers of healthcare and delays in the restocking of medical supplies. Based on the technical capacity of these sub-centers as determined by our interviews, we found that improvements in the stock resupply system would be the most feasible solution, and these improvements were also perceived to be the most useful by health workers. Therefore, we designed a Visual Stock Indicator System for use in the Mandi District.

The VSIS will allow sub-center health workers to immediately notify the Zonal Hospital when they are in need of medical supplies, reducing delays in restocking and monthly closures of health centers for travel. We also proposed streamlining the process of filling stock orders by eliminating the CHC as a middleman, and by providing a pharmacist at the ZH specifically dedicated to responding to requests coming through the VSIS. Together, these recommendations will facilitate the communication between different health centers in the Mandi District, improving the availability and quality of healthcare for its residents.

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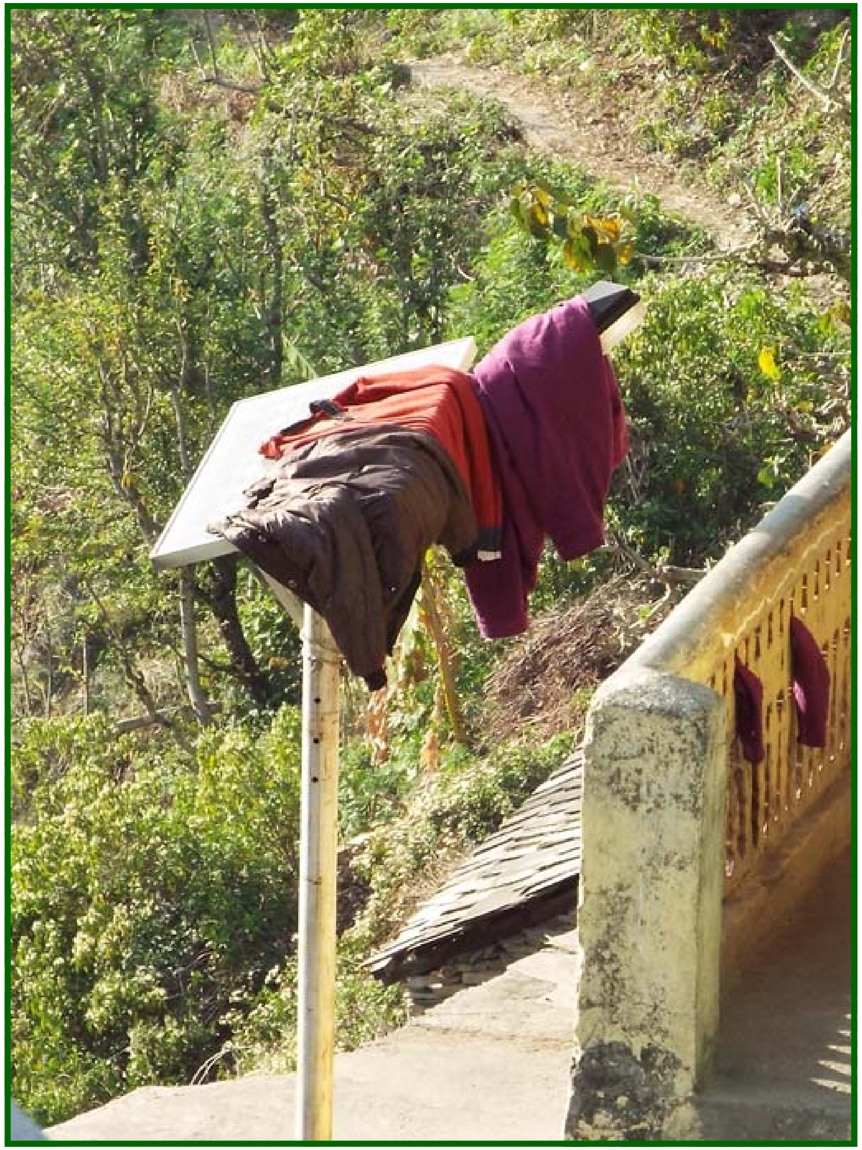
The full report and supplemental materials for this project can be found at

http://www.wpi.edu/E-project-db/E-project-search/search,

using keywords from the project title.

Additional information will also appear on the IIT's ISTP page which can be found at http://www.iitmandi.ac.in/istp/projects.html

Investigating Solar Street Lights in Mandi and Kamand



Abstract

Solar street lights are installed throughout Himachal Pradesh, India to promote small-scale solar, but many are broken. We disassembled lights and conducted interviews with residents and experts to understand the relevant factors, finding that the street light program suffers from inadequate maintenance and that solar is often not the best lighting choice. Finally, we piloted a training program for residents to perform light diagnosis and developed an appropriate technology rubric for selecting evening lighting solutions for Mandi's slums.

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The cloudy state of small-scale solar in Himachal Pradesh

Solar powered street lights have been installed throughout Himachal Pradesh by the Himachal Pradesh Energy Development Agency (HIMURJA). Installations range from small-scale village settings to urbanized centers such as the town of Mandi. These lights are useful since they operate even if the local grid is down, can be installed in remote areas, and promote energy resilience within a community. However, as seen in Figure 1, many solar lights have been in disrepair for years. This may contribute to lowered community appreciation of solar technology. Understanding how they are maintained, why these lights fail, and how residents perceive their usefulness is key for assessing the benefits communities receive from solar street lights and possibly for the future adoption of small-scale solar in the region.

The state of Himachal Pradesh wants to increase the use of solar power, but adoption has been slow. While there are a few communities that do not have adequate electricity, 99.7% of villages in Himachal Pradesh are connected to the power grid (Central Electricity Authority, 2015B). Over 75% of this power is derived from hydroelectric sources (Central Electricity Authority, 2015A). While the abundance and renewable nature of hydroelectric power make it an attractive option, infrastructure development has resulted in community displacement, environmental damage, frequent blasting, and geographically consolidated power generation (Times of India, 2013; Thukur, 2015).

Figure 1. A broken solar street light with a missing battery

Recognizing these vulnerabilities, Himachal Pradesh has developed a solar power policy to diversify its energy supply. Solar panels do not have the geographic restrictions associated with hydroelectric power generation, and can be used anywhere with ample sunlight. Even at a small scale, solar systems can bolster energy resilience within communities and reduce dependence on any one source. Small-scale systems like street lights provide potential for building capacity within the community for maintenance and repair, reducing reliance on external and often unreliable government services. Communities and government both play a role in the development of small-scale solar systems. Our research focused on understanding the social and technical factors necessary to improve and support these systems.

Solar systems in India: history and progress

Solar electric systems can generate power either indirectly with concentrated solar power (CSP) systems, which use the sun to generate heat and drive a turbine, or directly with photovoltaic (PV) systems, which use the physical properties of semiconductors to directly create a voltage (see Figures 2 and 3) (Singh, 2013). The lack of moving parts, rugged design, long effective life, and modular nature of PV give these systems low maintenance costs and high reliability, making solar ideal for off-grid applications. Solar has also found uses on the electric grid. Grid-connected systems are becoming more feasible as the production cost of PV panels drops, but solar power is still typically more expensive than electricity from conventional sources. The energy conversion efficiency of solar cells is typically around 14 - 19%, while large hydropower installations like those in Himachal Pradesh can be as efficient as 90% (Razykov et al., 2011; U.S.

Figure 2. Parabolic mirrors focus the sun at a 50 MW CSP installation in Rajasthan, India (Pearson, 2013)

Figure 3. A 4 MW PV installation in Tamil Nadu, India (Wikimedia Commons)

Department of Interior, 2005). Nonetheless, there is rapid growth of 30 to 40% annually in the global PV industry (Razykov et al., 2011).

For India as a whole, the benefits of solar power outweigh the drawbacks. In 2010, the national government announced the Jawaharlal Nehru National Solar Mission, a plan to grow India's solar power output from nearly non-existent to 20 gigawatts by 2022 through a combination of on and off-grid systems. The mission identifies solar as a secure, scalable, and renewable alternative for India's growing energy needs (Ministry of New and Renewable Energy, 2010). While solar is a good fit for India as a whole, the situation is less clear in the state of Himachal Pradesh due to plentiful cheap hydroelectric power (see Figure 4). However, in its 2014 solar power policy, the state recognized the environmental concerns associated with hydroelectric power, and that solar is important "to reduce the vulnerability of the system" (Government of Himachal Pradesh, 2014, p. 3). This vulnerability extends to individual communities, which should be protected from reliance on a single system.

HIMURJA supports this diversification by promoting and popularizing new and renewable sources of energy in the state. One component of the HIMURJA plan is the distribution of solar PV street light systems. As of 2014, there were 44,338 solar street lights in the state, along with 22,586 solar interior lights and 32,649 solar lanterns (Singh, 2014). Street lights are widely distributed throughout the state, including in villages, along roadways, and in concentrated installations at urban centers. The street light systems can introduce communities to solar power, and are a good fit for regions that are "electrified" but have unreliable or unstable grid connections (Jain et al., 2015).

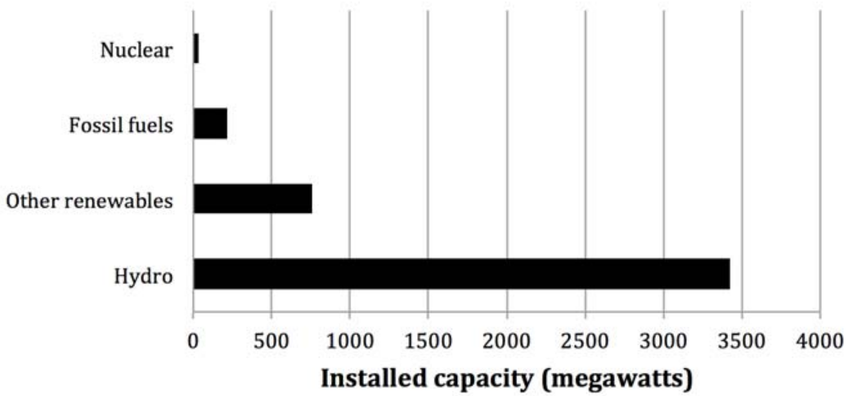

Figure 4. Installed capacity of power utilities in Himachal Pradesh (Central Electricity Authority, 2015A)

While solar street lights are widely installed, they are not well maintained. This may be due in part to a lack of planning or perception of benefits among local residents. Recent reports indicate that residents seem to lack knowledge about the full benefits of solar power, but are responsive when informed (Mercom Communications India, 2014). According to one study, the government has also not been informative about the solar subsidies available to individuals (Kumar, 2014). Another report from India found that more than 70% of residential respondents showed some favour towards solar panels with negligible opposition, but also that respondents held many misconceptions about the technology (Mercom Communications India, 2014).

With these issues in mind, community involvement and acceptance is key for successful implementation of renewable technologies. A case study with residents of a community in Germany indicated that participants were more accepting of new technology if they were actively involved in the entire implementation process in collaboration with local authorities (Zoellner, Schweizer - Ries, & Wemheuer, 2008). A lack of communication can result in reduced quality of life for residents by "undesired changes of the landscape, by noise, or by transport issues" (Zoellner et al., 2008, p. 1). While this review evaluated German respondents, many of the concerns that residents face are independent of cultural and socio-economic conditions. Without proper communication between stakeholders, Mandi norms, infrastructure, and reliability. In addition, stakeholders themselves are often capable of learning how to install and maintain solar systems, but simply lack the training to do so. Barefoot College, a training institute in India, has shown “that both illiterate and semi-literate men and women can fabricate, install, use, repair and maintain sophisticated solar units through basic knowledge share and hands-on practical training” (Barefoot College, 2015). Teaching rural residents to perform maintenance on their own better positions their respective communities for reliable, sustainable small-scale solar.

Methodology: technical analysis and interviews

Our goal for this project was to use solar street lights as a model for understanding the social and technical factors that impede continued adoption of small-scale solar technology in Himachal Pradesh. We broke this goal down into three objectives with accompanying strategies shown in Figure 5.

Isolated solar street light systems are currently installed in many locations throughout the region, including on the Indian Institute of Technology (IIT) Mandi campus, at several temples in Mandi town, and in surrounding villages. We performed a rapid assessment of the reliability of several installations by counting and labeling the non-functional lights at night. We disassembled several non-functional campus lights and measured their technical characteristics. These systems consist of three major components: a solar PV panel, a battery, and a light fixture with enclosed charging circuitry. We measured the open circuit voltage of the panel and battery, as well as the charging voltage from the light fixture. We also checked for continuity in wires connecting circuit elements. These measurements were used to diagnose which component in the light was faulty. Voltages and continuity were measured using multimeters available on campus.

We used semi-structured interviews with residential subjects to learn about the local perception and awareness of solar street lights (see Figure 6). Interviews were conducted in the villages of Nehri, Katindi, Nisu, Dhuki, Dudar, Sandoa, Kataula, the temple at Prashar Lake, and the slums in Mandi Town with travel arranged through the IIT. Samples of convenience were used in all locations along with snowball sampling where applicable. IIT students conducted the interviews and translated the responses. Interview questions captured basic demographic information, awareness and perception of solar street light systems including their history at the site, and level of understanding of photovoltaic technology itself. With permission, smartphones were used to record audio for reference. All records were securely stored and numeric identifiers were used instead of names.

We also conducted a semi-structured interview with an expert at HIMURJA in Mandi Town about the state of solar deployment in the region, its challenges, and suggestions for improvement. This interview was designed to provide more background and context to the problems described by residents in earlier interviews.

Finally, we used the knowledge gained from light disassembly and interviews to develop educational materials suitable for training local residents how to diagnose and repair broken solar street lights on their own. We tested these educational materials in the field by returning to some of the villages and working with local residents to follow the instructions and

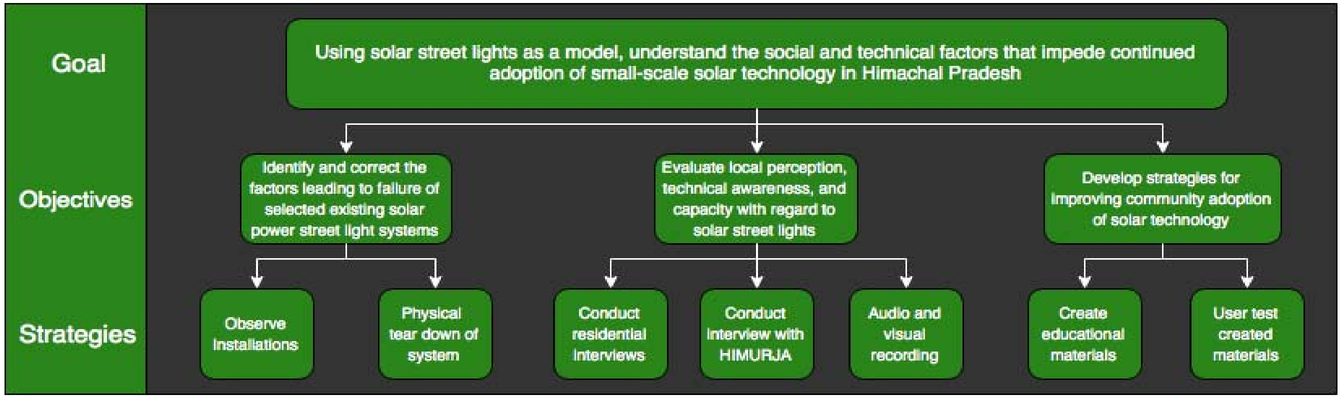

Figure 5. Outline of goal, objectives, and strategies

Figure 6. A site assessment in the village of Dudar

diagnose their solar light. These tests were video recorded for later analysis.

Results and Discussion

Through interviews, technical analysis, and pilot testing of educational materials we developed a broad understanding of the social and technical factors affecting solar street light adoption in the Mandi and Kamand region. Here we present the results of each objective followed by discussion of these results.

Objective 1: Understanding technical causes of light failure

We disassembled the three failing lights on the IIT Mandi (Kamand) campus to understand the technical reasons why they failed. We observed three distinct issues with the systems. The first system had a failing battery and was not able to hold a charge. Simple checks across the terminals of the battery with a multimeter verified that it could not produce a voltage under load. After replacing this battery with a battery from a working light, we observed that the light was functioning properly after a day of charging in the sun.

The second system had a simpler issue. Initial voltage checks on the panel and the battery were good, meaning the problem likely existed in light fixture circuit itself. After opening the fixture, we observed that the connection between the lightbulb and its socket was not clean. Dirt likely entered the fixture through poorly sealed electrical tape after the fixture was previously opened. The light worked properly after cleaning the connection and realigning the bulb.

We were unable to diagnose the exact issue causing the third system to fail. Battery voltage was good, and while the panel voltage was relatively low, this was acceptable given the light's occluded position and cloudy weather during testing. The electrician who assisted us suspected the light fixture circuit was faulty, but there was no visible damage. With more time we could have fully diagnosed the problem, but limited time and resources prevented a complete investigation. The electrician also noted that if the circuit was the problem, he was unsure how to find a replacement, which could make it difficult to repair.

Objective 2: Local perceptions, technical awareness, and capacity

Most interviews were ultimately conducted in small groups, resulting in collective results rather than individual perceptions. In sum, we conducted 39 site interviews with 61 participants. 27 of the interview sets were conducted in 8 local villages and historical sites that have solar street lights installed, 8 interview sets were conducted in and around the Bhimakali Temple in Mandi Town, and 4 interview sets were conducted in the slums of Mandi Town near Victoria Bridge. See Figure 7 for a summary of results.

All village sites were well electrified. Most reported 24-hour electricity with only 14 out of 39 interview sessions reporting some power loss. 10 of the 14 sessions reported mild semi-regular power cuts lasting for less than two hours a day, with the remaining 4 sessions at Prashar Lake reporting regular power except for outages lasting several days during severe weather. Given this reliability, it was not surprising to learn that most respondents did not depend on solar street lights for regular lighting needs. Only one site, the Mandi Town slum area, had no electricity at all.

When asked about solar power, 39 of 50 interviewees understood the concept and had a general understanding of how it worked. Men were more likely (89%) than women (54%) to understand the basic idea of solar power, but otherwise there were no clear distinctions based on age or level of education. Slum residents had a solid understanding of solar power despite most of them lacking any formal education. Familiarity with solar power appears to have much more in common with previous exposure to solar-based systems than educational background.

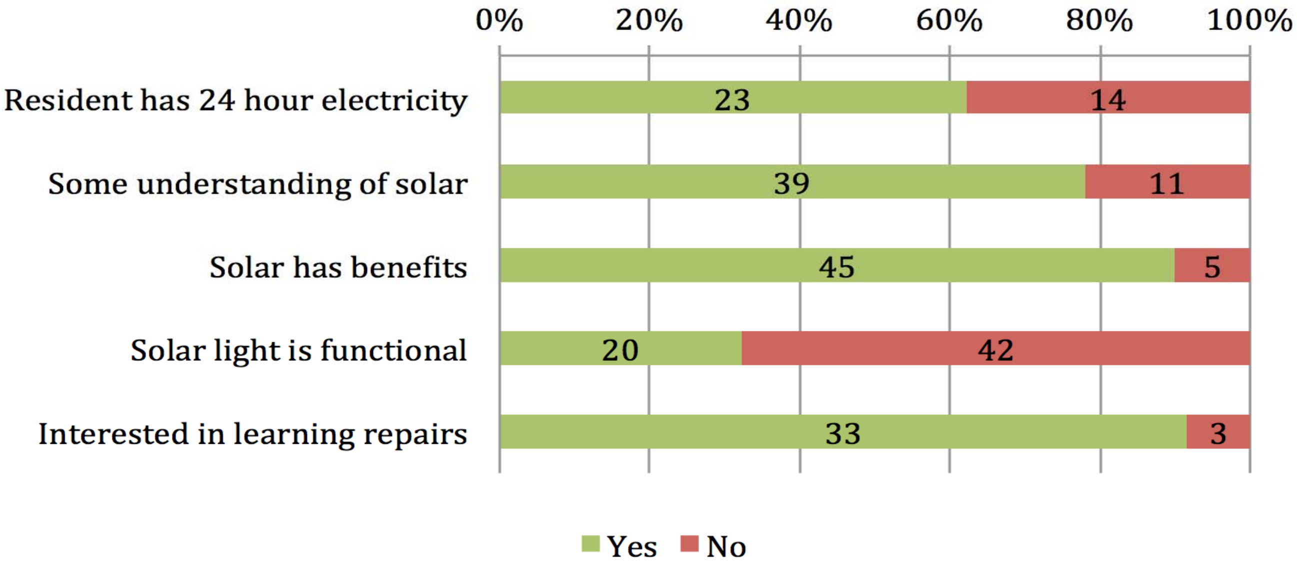

Figure 7. Summary of major findings from residential interviews

When asked about benefits of solar power, 45 out of 50 respondents supported solar power based on its low maintenance, low cost, perceived reliability, and easy installation. Cost was an important factor for many residents. Because it is off-grid, solar lighting is effectively free when compared with home lighting powered through the grid. 5 respondents believed that there were no real benefits of solar power, demonstrating a potential disconnect between the actual benefits of solar and the communities using it. Though in most communities the lights were not strictly needed, stakeholders still found the lights beneficial and wanted them to work. Slum residents in particular described the light as highly beneficial for their school-aged children to study at night. All interviewees supported the idea of more solar street lights, notably to improve safety and productivity, but again cost was a major concern. Several residents supported the idea only if the new lights were free of charge or heavily subsidized.

Despite this positive perception, the lights are not well maintained. Of the 62 solar street lights we encountered, 42 were reported as nonfunctional by respondents. 14 of the 25 lights at the Bhimakali Temple were broken, 12 of the 21 lights in villages and slums were broken, and all of the 16 lights at Prashar Lake were broken and missing batteries (see Figure 8). Most of the village lights were installed 4-6 years ago by HIMURJA, but there were some notable exceptions. Nehri village purchased its one light as a community 10 years ago, and the slum community purchased its light only one year ago. Both of these community purchases were in response to a lack of electrification at the time. The lights became less of a necessity as villages became electrified. The lights that fail are typically reported to have stopped working within 1-2 years after installation. Worse, respondents reported that most of the lights have never been officially maintained. Only the light in the slum community had regular maintenance performed by the municipal government. The lights at Prashar Lake were failing for a year before the deputy commissioner took action by removing the batteries for repair, but the batteries are still missing after six months.

While official support is lacking, there is potential to build capacity for solar street light maintenance within the communities themselves. Of the 36 individuals we asked about interest in learning to diagnose or repair these systems, the vast majority (33) expressed a willingness to learn. Exceptions came mainly from Mandi Town residents who felt they were too busy and would rather have the local government perform maintenance. However, the need for solar street lights is less pressing in these urban areas. We observed one situation in Dudar village in which a resident had connected the lighting fixture of a solar street light to his home's electricity after the light stopped working, and maintained it himself for 5 years. Similarly, the residents of Nehri village bought and assembled a light themselves. These actions demonstrate the latent capacity that exists within these communities.

We also interviewed an expert at HIMURJA in Mandi Town to understand the issues surrounding solar street lights from an institutional perspective. HIMURJA itself does not directly install or maintain lights, or create policy, but instead acts in a coordinating capacity to implement renewable power initiatives from higher-level government agencies among local companies. Local government officials provide lists of eligible communities to HIMURJA, which then collects bids from installation companies. New lights cost Rs 15,360 for a light emitting diode (LED) type light or Rs 18,365 for a compact fluorescent light (CFL) type light, but under previously existing subsidies communities pay only 10% or less of the total cost. After installation residents receive basic manual instructions about proper care and procedures for reporting broken lights.

Figure 8. Broken light at Prashar Lake

The lights are under warranty for 5 years. During this time, residents can either contact HIMURJA directly by phone or contact their local government to report a broken light. HIMURJA will send a technician out for repair and cover all costs. Battery failure is reportedly the most common reason for repairs, but when other parts fail they often must be ordered from Chandigarh, a city nearly 7 hours away by vehicle. The process for contacting HIMURJA is outlined below in Figure 9.

After the warranty period has expired, HIMURJA is no longer responsible for the lights' maintenance and they often remain in a state of disrepair because villages cannot afford to fix them. HIMURJA believes the maintenance process works well, and supports the idea of building maintenance capacity within communities themselves, especially after the warranty of the light has expired. Building this capacity reduces the burden on HIMURJA and makes the installations more self-sustaining.

Objective 3: Development of strategies to improve adoption of solar

We analyzed data collected from our first two objectives and identified strategies to improve the viability of solar street lights in the communities they serve. The strategies were vetted by experts at the IIT-Mandi and further refined. We also created prototypes for educational materials featuring diagnostic and repair instructions. We piloted the instructions to verify their effectiveness, and to ensure that they are easily understandable and beneficial to local stakeholders. Finally, we conducted additional interviews in the Mandi Town slums to develop an appropriate technology rubric for further development of evening lighting solutions in the community.

Discussion

There are several potential reasons why solar street lights have not been maintained in the Mandi and Kamand region. Although residents enjoyed the benefits of solar lighting, they did

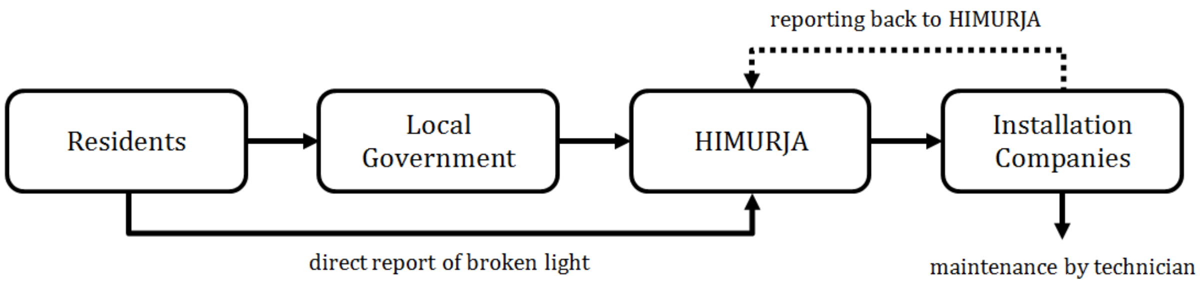

Figure 9. Overview of the process of reporting a broken light to HIMURJA

not always follow through by reporting failures to appropriate authorities. Without adequate maintenance, lights can fail relatively quickly. Regular upkeep is critical in supporting the lighting infrastructure. When residents did make an effort to try to get broken systems repaired, the lights were frequently out of warranty, but residents did not know that this prevented free repairs. After the warranty expires, beneficiaries are required to pay for repairs out of pocket which means that lights are much less likely to be fixed.

Even when communities try to take an active role in maintaining their solar lights, the response is usually weak. Residents of Dudar village and a shopkeeper near Bhimakali Temple complained to their local government, but received little or no assistance. At Prashar Lake, all 16 lights were failing. Outreach by nearby residents to responsible agencies resulted in the batteries being taken for repairs. However, six months later, the batteries are still missing and residents have received no information about when repairs will be completed. These failures are likely due to a lack of communication between beneficiaries, HIMURJA, and companies. Finding where these communication breakdowns occur requires further study.

Residents were sometimes unsure of where to report broken lights even though HIMURJA claimed distribution of contact information. The HIMURJA representative also said that companies educated residents about the systems and proper maintenance techniques after installation. However, few residents knew about this contact information or maintenance procedures. Given that this information is distributed during installation, it is likely that knowledge of the systems does not persist over time due to too few individuals receiving or sharing the training. Both residents and HIMURJA support local maintenance, and clear potential exists in this area for building capacity.

Finally, many residents enjoyed solar street lighting due to its low cost when subsidized, as well as its other benefits, including safety and extended evening activities. These features are not restricted to solar street lights, but solar is a good fit in the current regulatory framework because of heavy subsidies. Rural residents tend to care more about the cost of the system than other features such as grid independence and environmental friendliness. From a technical perspective, traditional street lighting may be a better fit for these residents because it is less likely to be plagued by the maintenance issues of solar street lights and be more reliable in the long run. Solar street lighting is a natural fit in areas like Prashar Lake where power loss is common, but in most locations the choice is not as clear. Communities would benefit from alternative evening lighting solutions that are more carefully tailored to their individual needs.

Project Outcomes

Our research led us to a broader understanding of the issues surrounding solar street lights in Himachal Pradesh and a realization that solutions to the true problem of evening lighting may lie outside solar technologies. We developed three key project outcomes:

- A critical review of the existing solar street light program and suggestions for how its effectiveness could be improved
- A pilot program for training local stakeholders how to diagnose and potentially repair existing lights that are out of warranty
- A case study of the evening lighting needs of the Mandi Town slum community, including the development of an appropriate technology rubric and proposal of technological solutions

Solar street lights in Himachal Pradesh: a critical review

HIMURJA's solar street light program has successfully distributed over 40,000 lights throughout Himachal Pradesh, increasing the visibility of small-scale solar technologies in many communities. These lights bring highly desirable benefits, including safety and extended evening activities. As discussed, solar street lights are also a good fit in areas with unreliable grid connections, like Prashar Lake. Unfortunately, in practice these benefits often last only a few years before the lights fall into a state of disrepair.

In theory, the lights should be well maintained during the five year warranty period after installation through HIMURJA's partnership with local companies. During this time, residents are able to report broken lights either directly to HIMURJA or to local government and receive repairs free of charge. In practice, however, the program appears to be mired in bureaucracy and poor accountability. Reporting from maintenance companies back to HIMURJA is poor, local government can fail to take action, and residents are often unaware of how to report a broken light. Additionally, the five-year warranty period is far too short for most communities. If properly maintained, a solar street light could bring benefits to local communities indefinitely, much like traditional street lighting.

Cost of lighting is a major factor in most communities. With large subsidies available, solar street lights initially appear attractive. But given their history of poor maintenance, communities can easily end up losing the benefits they seek. Nearly every community we studied was well electrified by the power grid, with minor power cuts lasting no more than two hours per day. This finding is consistent with state level reporting on village electrification. Given the reliability of the electric grid in most areas, traditional grid-connected street lighting is a technologically superior choice. Because they are connected to the grid, traditional street lights do not need to generate or store energy and therefore have fewer components that could fail, resulting in increased long-term reliability. Traditional lights carry associated monthly bills from the state electric board, but are much more likely to bring long-term benefits to the communities they serve. While solar street lights have the potential to build energy resilience in rural communities when well maintained, the poor implementation of the solar street light program actually results in reduced energy resilience and quality of life.

Solar lighting is a technologically superior choice in a few areas, like Prashar Lake where power is lost for weeks during the snowy season. There should be an increased focus on long-term maintenance and accountability at these sites, but building this capacity is a complex problem that is unlikely to be solved soon. If more solar street lights are installed in Himachal Pradesh, the site selection process should be modified to favor communities that would see the most benefit from solar technology by incorporating factors like community acceptance, the reliability of the existing grid connection, if any, and already installed evening lighting solutions.

Ultimately, the failure of solar street lights to bring lasting benefits to communities in Himachal Pradesh can be viewed as a misalignment of national energy objectives and the needs on the ground in the region. The national government wants to build India's solar capacity in order to reduce dependence on fossil fuel sources and bring electricity to un-electrified villages. Himachal Pradesh, however, already has abundant, cheap, and renewable energy from large hydroelectric power installations, and a well-developed electric grid with near 100% penetration in rural villages. Himachal Pradesh would be better served by developing incentive programs that promote regionally appropriate technologies that better serve community evening lighting needs, but we recognize that such change is difficult within the national framework.

Improving community maintenance capacity through local education

Despite the shortcomings of the solar street light program, many of the failing lights that are currently installed could potentially be diagnosed and repaired by residents. While better official light maintenance is the ideal solution, community maintenance education can create immediate and lasting impact by restoring the benefits of existing lights. HIMURJA identified battery failure as the most common cause of light failure. Fortunately, this case is simple to diagnose and new batteries can be easily sourced from local car parts suppliers. However, our own research revealed that some units suffer from faulty circuits and other more difficult to diagnose failures.

We developed an educational diagnostic guide that can be affixed to the inside of the battery compartment (see Figure 10). This guide was designed to be easy to follow with only basic literacy and a minimal set of tools. The most complex tool required is a multimeter, but in our fieldwork we found that this tool is commonly available in local hardware stores. Using the guide, users can diagnose failure in the solar panel, light fixture, battery, or wiring. Failures of the battery or wiring can be resolved within a community without special orders for expensive parts. Affixing the guide to the inside of the battery compartment protects it from the weather and keeps the information at the point of use, avoiding community knowledge loss over time.

We pilot tested this guide with 5 users in the villages of Dudar and Nisu as well as on campus to assess its usability and effectiveness. Residents were provided with the guide and necessary tools and instructed to attempt to diagnose the solar street light. We were available to answer questions and assist.

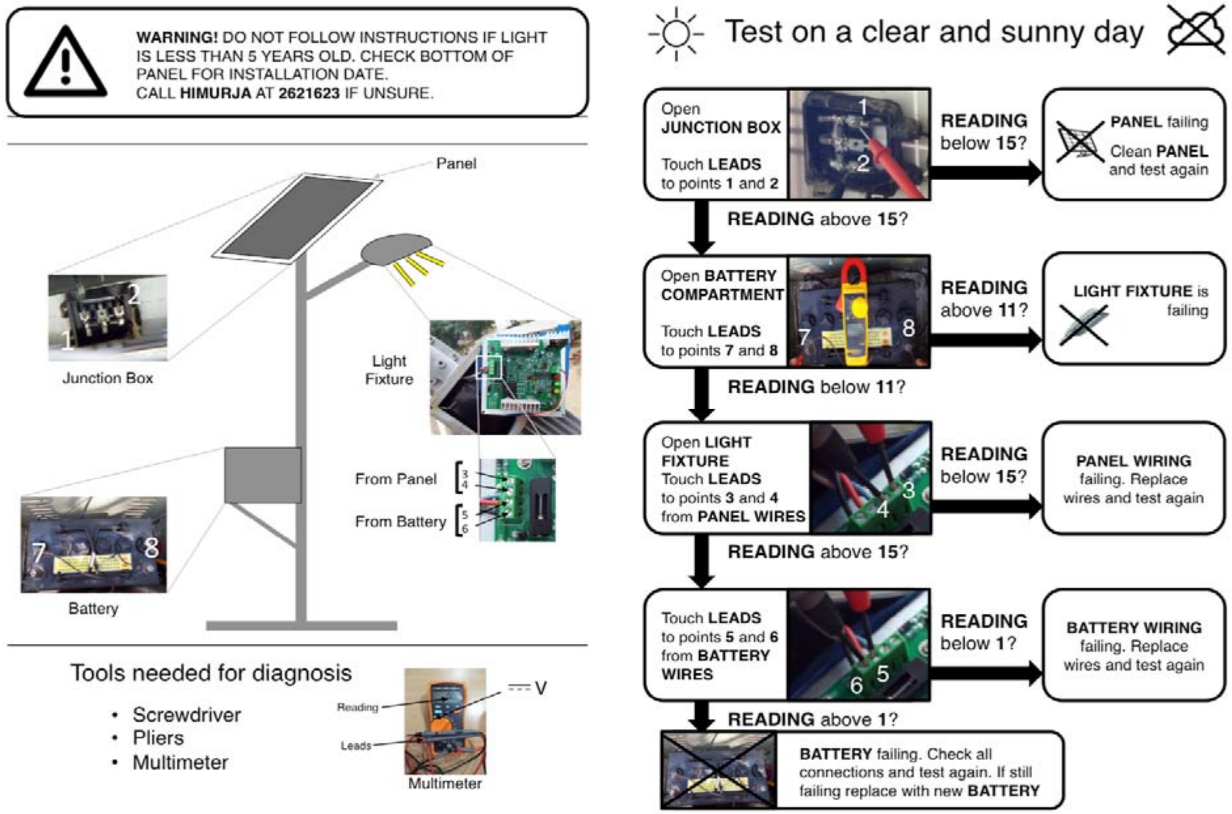

Figure 10. Educational diagnosis guide (English version)

4 of the 5 test users were able to successfully diagnose the light. The light in Nisu suffered from a broken light fixture and the light in Dudar had a broken panel (see Figure 11). In general, users found the instructions easy to follow and understand as measured by a five point Likert scale. Measuring the voltage from the panel and battery was straightforward, but measuring the voltages inside the light fixture proved more challenging for some users. They initially struggled to identify the proper terminals to connect the multimeter to, but the numbering of connection points and close-up photos of multimeter connections usually resolved the ambiguity. This problem is compounded by the fact that a wide variety of solar street light designs exist in the field, and our small team did not have the resources to design an educational guide for every design. This forces users diagnosing a different model to have a higher level of technical literacy. Ideally a separate set of instructions would be developed for each model.

Despite their successes, users were not always confident in their ability to diagnose a light in the future. One user said that he would need to follow the instructions at least 3 more times in order to feel confident. Building confidence with a purely paper-based educational solution is difficult, and a manual walkthrough of light diagnosis would clearly be better. Coupling instructions affixed to the inside of the battery compartment with the manual training already present during installation could bring both the

Figure 11. Instruction usability testing in Nisu

confidence benefits of manual training and the persistent knowledge benefits of permanent instructions to local communities.

None of the test users already owned a multimeter, and most were concerned about their ability to obtain one. However, this may have more to do with a lack of familiarity with the tool than a true lack of availability. We found multimeters for sale during our fieldwork, and residents would likely be able to obtain one if needed. Users were confident in their ability to obtain other tools and repair materials like wire and car batteries.

All users agreed that the instructions should be included with solar street lights and that doing so would improve the maintenance of the lights. However, users also highlighted some of the larger issues surrounding the solar street light program. One user explained that because the community doesn't really need the lights, he would only try to repair a light if he knew there were government funds available for repair costs, but these funds are unlikely to ever be available. Given these concerns, the instructions will prove most useful for communities with a strong dependence on their solar street lights due to intermittent or no grid power.

Evening lighting needs in the Mandi Town slums

Many of the failures of the existing solar street light program stem from a failure to understand the needs of the communities the lights are being installed in. Residents appreciate the low cost, safety, and productivity benefits that solar street lights bring, but these benefits are not unique to solar street lights. A top-down approach that dictates technological choices fails to consider the evening lighting needs of individual communities. To better understand these needs and develop more appropriate technologies, we conducted a case study in slums of Mandi Town. This community is particularly interesting to study because it is not currently electrified, has expressed desire for increased evening lighting, and has strong constraints on the cost of a potential solution.

We conducted semi-structured interviews with 9 residents of the Mandi Town slums to understand current evening lighting practices and requirements for new lighting technology including cost, usage, technical literacy of users, maintenance requirements, environmental suitability, and usability. Using the interview responses and our background understanding of the problem, we developed an appropriate technology rubric suitable for selecting and developing improved evening lighting solutions for the slum community (see Figure 12).

We found that residents currently spend around Rs 500 per household per month on candle lighting, but are not satisfied. They buy candles at the local market daily or weekly, use 3-5 candles each night and get light for 3-4 hours. Residents were unhappy with the light output of the candles and the color of the light. Weather is also a major factor, as candles in the open slum dwellings can easily blow out in wind or rain. Providing light for children to study at night is the most common use of lighting, but the light is also used for other activities like cooking and games. Residents felt comfortable with basic maintenance of an improved lighting solution, but did not feel confident diagnosing electronics.

Relevant Need	Economic limitations	Cultural compatibility
• Need light primarily for children to study at night • Need light for other activities like cooking and games	• Rs 500 per Month but low or no recurring cost preferred • Rs 500 – 1000 one time purchase • Rs 2000 group purchase	• Light can be purchased locally • Light is simple to operate for all social groups • Light can function as a drop-in replacement for candles • Light is legal by Indian law
Technical literacy	**Environmental responsibility**	**Usability**
• Includes maintenance instructions in Hindi • Light last at least 1 year without maintenance • Minimal tools required for maintenance • Minimal technical understanding for maintenance	• Works in extreme wind or rain • Works in extreme temperatures • Does not produce harmful waste products indoors • Minimal technical understanding required for maintenance	• Does not require grid connection • Produces white light • Bright enough to light a small work area for reading and writing • Lasts 3-4 hours per night • Performance of light is consistent over time • Can be hung/attached to ceiling or moved • Can charge mobile phones

Figure 12. Appropriate technology rubric for Mandi slum lighting

Some residents were also interested in having mobile phone charging as part of the lighting solution.

Based on our rubric, we developed a prototype solution for improved evening lighting. We selected solar lanterns as a good fit for the community due to their reliability, low recurring costs, robustness in bad weather, higher light output, and light color. Solar lanterns have been used elsewhere in Indian slums for replacing kerosene lanterns (The Indian Express, 2015) and quality standards concerning reliability and light output exist for the technology, avoiding some of the pitfalls observed with solar street lights (Lighting Global, 2016). They are also a relatively low cost technology, especially over time.

We found solar lanterns for sale in Mandi Town for Rs 1,835 each. These lanterns provide 10 times the light output of 3 candles, provide mobile charging, and last for up to 15 hours each night. While the cost is prohibitive for individual purchase, several households would be able to buy one of these solar lanterns as a group. Individual purchase would also be feasible if payment plan options were available. This business model has been used in other Indian slum lighting projects (The Indian Express, 2015). Overall, the lantern scored 21 out of 24 on our rubric.

We provided two of these lanterns to the community for evaluation and testing. Community members strongly preferred the lanterns to candle lighting. When we returned to the slum two days later to evaluate the residents' opinions of the lanterns, we found that the community had started constructing a new school building to hang the lights in (see Figure 13). This kind of building was not present previously. Latent capacity existed, and providing evening lighting was the push needed to unlock it. When we told the residents how much the lights cost, they expressed a willingness to purchase more lights as a group at that price point in the future. There is clear potential for continued growth, and it appears that a simple lack of knowledge about alternative lighting solutions and their availability was holding the community back.

Cheaper solar lanterns are also available commercially, running as low as Rs 500, but we were unable to find these products for sale locally. These lights typically have reduced light output, sometimes not much more than several candles. However, they can still be useful by focusing the light better than candles, creating adequate task lighting in a small area the size of a few sheets of paper. Maintenance is also less of a concern with prices this low, as it would be feasible for community members to simply buy a new lantern if their current lantern fails. These lanterns may be more applicable for individual homes. Purchasing these cheaper lights would likely require the community to place an order as a group with a local store.

Figure 13. School under construction

While our prototype solution is not perfect, the design together with our appropriate technology rubric provides the first step for improving evening lighting in the Mandi Town slums and throughout the region.

Conclusion

Solar street lights are valued by local communities because of the safety and productivity benefits they provide, especially in areas with intermittent or no access to the electric grid, but our study revealed a pattern of poor maintenance and failing lights due to poor program implementation and a failure to consider the appropriateness of the technology. Educating residents about simple procedures that can be used to diagnose and potentially fix common causes of failure in existing lights enables these communities to restore lost benefits and build internal capacity for small-scale solar technologies. Looking forward, new evening lighting initiatives should carefully consider the needs of local communities and develop solutions that will enable these communities to benefit from evening lighting for more than just a few years. With proper consideration of appropriate technologies, evening lighting can be a reliable way to create a brighter future for the most vulnerable communities in Himachal Pradesh.

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The full report and supplemental materials for this project can be found at http://www.wpi.edu/E-project-db/E-project-search/search using keywords from the project title. Additional ISTPs can be found at http://www.iitmandi.ac.in/istp/projects.html

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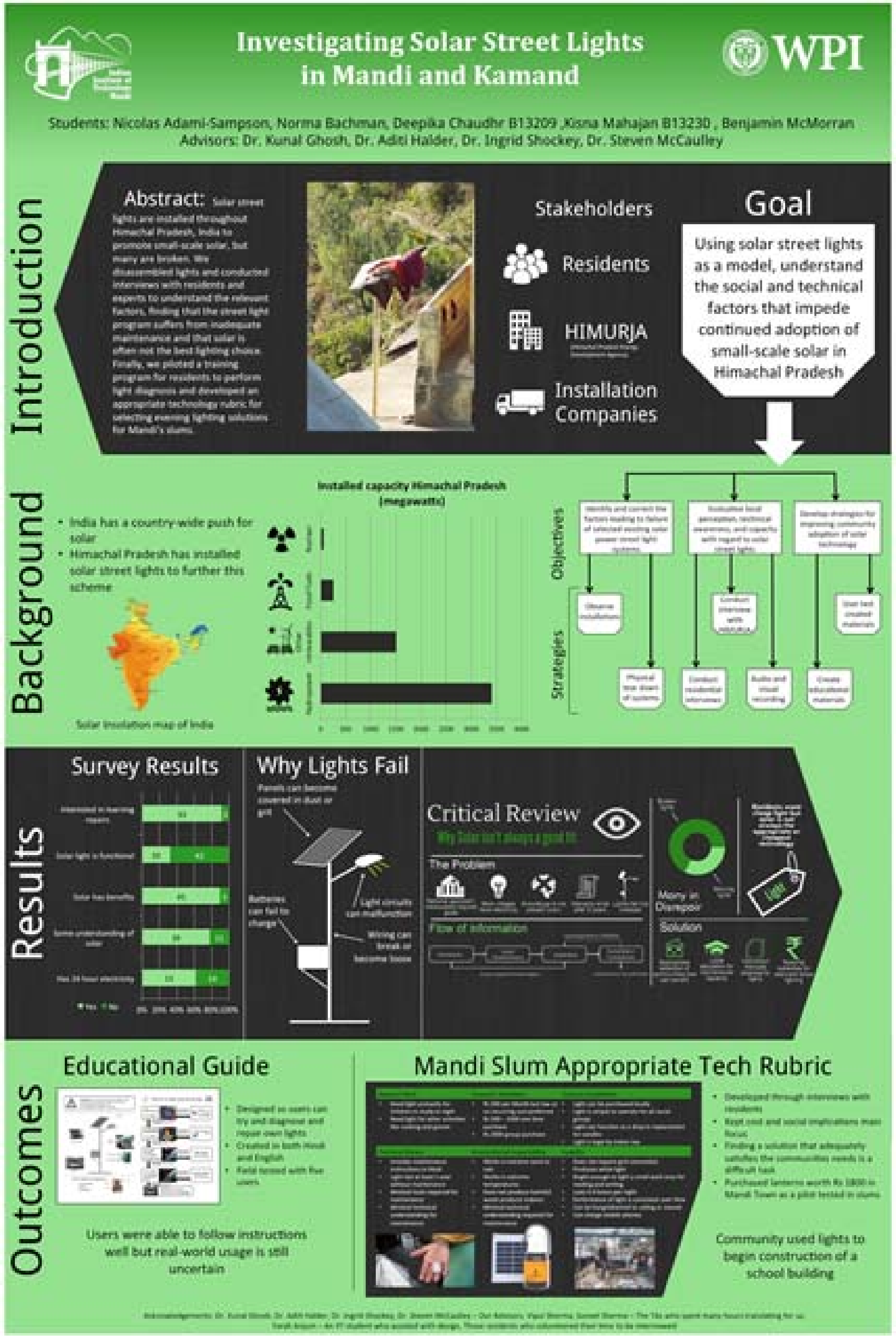

Evaluating Waste Management Systems: Kataula and IIT-Mandi

Abstract

Mandi District in Himachal Pradesh India is experiencing increased waste generation due to economic growth and the expansion of the Indian Institute of Technology-Mandi campus. This project's goal was to develop recommendations to improve solid waste management at the IIT-Mandi campus and village of Kataula. Data on local practices, waste composition, and resident preferences were collected using waste audits and interviews. Findings indicated a need for better separation techniques on campus and a waste collection system in Kataula.

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WPI

The Growing Challenge of Waste Disposal

Mandi District in the Indian state of Himachal Pradesh sits at the crossroads of three national highways. It has become a popular trade and tourist center in the state (Directorate of Census Operations in Himachal Pradesh, 2011). Consequently the city has been growing rapidly. Mandi District is also the new home of the Indian Institute of Technology (IIT-Mandi) campus. With the area serving as a hub for tourism, commerce, and education, a need has emerged for improved waste management practices in the Mandi district. Improper waste management can be hazardous to the environment, human health and the visual aesthetics in a region. Over the last few years, the state government has begun a push for more sustainable waste management practices, yet success has been sporadic. A study conducted by Ascenso Enviro Private Limited in 2008 identified an inadequate regional waste management system characterized by unregulated dumping of trash from communal waste bins and a disorganized system of private disposal firms (Ascenso Enviro, 2008). A more recent IIT-Mandi study in 2014 found many of these issues were still unresolved (Panwar et al., 2014). Furthermore, the waste management systems in the campus and nearby villages need to be improved to prepare for the population influx that the growing IIT campus (see Figure 1) will bring. This will increase strain on the current waste system in which the majority of campus waste ends up at the Mandi municipal dump shown in Figure 2. Therefore, the goal of this project was to develop improvements for the waste management systems in the IIT-Mandi campus and the villages of Katindhi, Kataula, and Navlay. To meet our goal, at each location, we:

1. Documented local solid waste metrics.
2. Identified and assessed waste collection programs and infrastructure.
3. Gauged perceptions and practices with regards to waste management.
4. Developed a set of recommendations for improved waste management systems in the IIT-Mandi campus and the village of Kataula.

Figure 1: Map of the final plan for IIT-Mandi campus construction

Figure 2: A section of the Mandi municipal dump.

Local Context and Logistics

Current waste initiatives in the state

In response to the increase in waste generation, along with prompting from the national government, the authorities of Himachal Pradesh have begun to implement a number of initiatives which address the waste management issues in the state. The first national waste management policy was developed at the start of the century and is referred to as the Municipal Solid Wastes (Management and Handling) Rules, 2000. These regulations outlined the operational expectations for solid waste management from generation to disposal. Unfortunately, according to the State Pollution Control Board, municipal governments did not utilize or construct new infrastructure, as required this lead to the rules being largely ineffective (Directorate of Urban Development, 2015).

In an effort to mitigate some of this unhandled waste, the state of Himachal Pradesh banned the use of traditional plastic bags in 2009 (Deccan Herald, 2009). This focus on plastic waste reduction is important given that the growth rate of plastic consumption in India in

2006 was a high 16% per annum (Muthaa et al., 2006). The state government continued to tackle this issue by banning all non-biodegradable plastic cups and plates in 2011 (Daily News & Analysis, 2011). If these trends continue, waste composition in the region will begin to lean heavily into the biodegradable sphere. However, at the current moment significant amounts of biodegradable and non-biodegradable waste continue to accumulate in the region.

Stakeholders

The following Table 1 lists some of the major stakeholders in the region.

Table 1: List of major stakeholders and their connection to waste management.

Stakeholder	Connection
Households	Prevalence of waste poses health risks to locals
Shopkeepers	Waste buildup can deter shoppers and tourists
Medical facilities	Hazardous medical waste must be handled safely
Municipality	Local government involvement improves sustainability
State regulators	State Pollution Control Board oversees waste management policy
Waste companies	Financially invested in any new waste management system
Sweepers	Future systems should not negatively impact their livelihood

Logistics and infrastructure for waste management

The lifecycle of waste can be broken down into four major stages: waste generation, collection, separation, and disposal. In the following sections a number of systems for performing each of these tasks is discussed.

Generation

In the Mandi district's rural regions the main source of waste is agricultural, while in the urban areas the majority of waste is produced by residents and transient populations (Ascenso Envio Private Limitted, 2008).

There have been no statewide waste audits conducted for Himachal Pradesh. However, it is known that, despite the statewide ban on plastic bags, there is still a substantial quantity of plastic packaging waste present (Directorate of Urban Development, 2015, Panwar et al., 2014). The unregulated mixing of plastic waste with organic waste makes the waste unfit for recycling. A waste audit would, therefore, allow waste management officials to make decisions targeted to the region's waste composition.

Collection

When a formalized waste system is present, the collection of waste is the first necessary step. There are two forms of waste collection: primary collection and secondary collection. Primary collection, which is common in Mandi town, involves an individual paying an organization for the removal of waste from their property (Panwar et al. 2014). Secondary collection is a large scale government organized waste collection system. Unfortunately, such a system is expensive, and might not be feasible in the local villages of Mandi district (Wilson, 2012). A third option, utilized for example in Nakuru, Kenya, involves the combination of the two collection strategies mentioned above. This town suffered from waste disposal issues similar to those faced in the Mandi district, but managed to increase their waste collection from 20% to 64% over 16 years by changing the governmental role from operation to oversight of private waste management firms (Mwanzia, 2013). Such a system might be worth investigating for use in the Mandi district.

Waste pickup in Mandi and the surrounding villages is very sporadic and does not operate on a set schedule. Approximately 38% of Mandi residents receive collection services at their place of residence, the rest dispose of their own waste (Nexus, 2015). In the villages waste collection is often non-existent or informal. Therefore, as Wilson (2012) argues, to ensure success any formal waste collection system should work to incorporate the informal sector by organizing local rag pickers under government oversight or hiring them directly.

The collection of waste from public spaces such as campus grounds or a city park provides some unique challenges. Such collection is usually coordinated using public waste bins. The placement of these waste bins is a major consideration when designing the collection strategy. Trash bins and recycling bins are likely to be most effective when installed in areas that generate high volumes of waste. Ensuring waste bins are easily accessible and in high enough numbers also improves waste collection effectiveness (O'Conner, 2010).

The usage of public recycling bins, or a similar system, to facilitate source separation of waste can save waste management facilities the equivalent of millions of dollars (Rinkesh, 2009).

When considering source based separation bin location is an important consideration. Bins should be located within 12m (40ft) of any waste source to ensure proper usage (Environmental Protection Agency of Australia, 2005). With sufficient infrastructure, a source separation based system is preferable, if the local population accepts and implements the process.

Waste disposal strategies and challenges

Once waste has been sorted it must be disposed of in a safe and environmentally friendly manner. Where waste management procedures are not in place, the most common practice is to dump the waste in a local non-engineered landfill or river. Burning waste heaps when they become too large is also a common practice (Hodzic et al., 2012). Both strategies will cause the environment to become contaminated and full of dangerous substances called leachates (Melnyk et al., 2014).

A better alternative waste disposal strategy, for non-biodegradable waste, would be the use of engineered landfills. These prevent leachates from entering the soil and contaminating the environment. For biodegradable waste, another method is composting, which converts the waste into nutrient rich soil. Both of these methods can be used to generate biogas for energy generation (Ali et al., 2014, Ndegwa et al., 2001). Furthermore, a method commonly used is incineration, where waste is burned at high temperatures in order to generate energy. However, the health implications of incineration are still debated (Candela et al., 2015, Protano et al., 2015).

Considerations

As evidenced by the numerous topics discussed above, development of waste management systems requires an understanding of numerous topics from logistics to human behavior. The recommendations we developed for the Mandi region needed to take all of these into consideration. By conducting sufficient research into the needs of all key stake holder groups it was possible to develop recommendations that used the most appropriate processes to improve waste management in the region.

Methodology: Gauging Waste Metrics and System Effectiveness

The goal of this project was to develop models for waste management on the IIT-Mandi campus and the nearby villages of Katindhi, Kataula, and Navlay. A map of these locations can be seen in Figure 3, below.

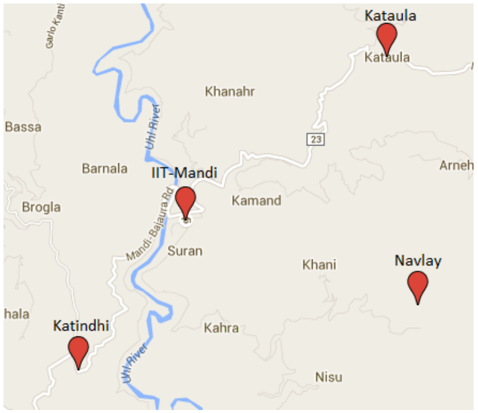

Figure 3: Map of the IIT campus and analyzed villages

To meet our goal, at each location, we:

1. Documented local solid waste metrics.
2. Identified and assessed waste collection programs and infrastructure.
3. Gauged perceptions and practices with regards to waste management.
4. Developed a set of recommendations for improved waste management systems in the IIT-Mandi campus and the village of Kataula.

Objective 1: Document municipal solid waste metrics

To gain an understanding of the waste that is generated at each location, we conducted a detailed site assessment and interviews. We also conducted waste audits on the IIT-Mandi campus and in the village of Kataula. This data was used to gauge the scope of the problem with regards to composition and quantity of waste, as well as the effectiveness of the current systems. The methods used are outlined in Table 2. The interview guide for this step can be found in

Table 2: The three methods used to collect waste metrics

Strategy	Purpose	Details
Site assessments	Gauge scope of problem	Map dumpsters and landfills assisted by local knowledge Identify areas of need
Interviews	Understand waste sources	Semi-structured Sample of convenience 50 local participants
Waste audits	Obtain quantitative data on waste composition	Approximate waste composition Approximate waste quantity

Appendix A and the waste audit data sheet can be found in Appendix B.

Objective 2: Evaluation of waste collection programs and transportation infrastructure

In order to evaluate existing waste management systems, we identified the staff and organizations responsible for collection and transportation of waste. Semi-structured interviews were conducted with collectors and managing organizations directly associated with the transportation of waste. See Appendix A for the interview guides used throughout the project.

Objective 3: Gauging perception, practices and preferences

The waste disposal practices of both villagers and IIT stakeholders and their preferences with regards to potential changes were evaluated in order to determine feasible alternatives. During the site assessments mentioned above, we observed and documented the waste disposal habits of locals. A series of semi-structured interviews were administered in an effort to reveal the current practices and attitudes, of both locals and professionals, with regards to waste management. A photo of one such interview is shown in Figure 4. This understanding was needed before the waste management strategies could be evaluated. Furthermore, it allowed us to determine the subjects' attitudes towards their own waste disposal habits. This information allowed for the identification of the driving factors behind these practices such as local norms, preference, or lack of options and resources. Finally, the purpose of conducting semi-structured interviews was to obtain information from individuals who might be reluctant to criticize the

Figure 4: The team after an interview with the Kataula school principal and physics teacher

waste management practices of their community. See Appendix A for the interview guide.

Objective 4: Development of recommendations

To develop a set of actionable recommendations to improve the waste management systems at each location, the collected data was analyzed and synthesized. The team modeled the flow of waste during standard disposal at the campus and a village. This model was used to help conduct a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis. This was used to develop effective recommendations utilizing each systems' strengths to address its weaknesses. A diagram of this overall process can be seen in Figure 5, on the right.

Results

This chapter outlines and discusses our on-site research findings by objective. Our research focused on three villages, Kataula, Katindhi, and Navlay, and the IIT campus.

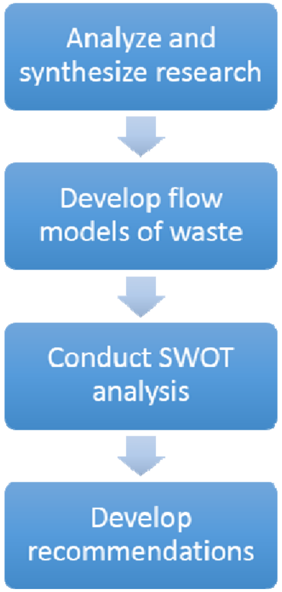

Figure 5: Process for developing recommendations

Objective 1: Documentation of municipal solid waste metrics

This section covers our observations and site assessments of the area, as well as metrics, collected from the IIT campus and three surrounding villages.

The team conducted a site assessment of the IIT-Mandi campus. Waste quantity, litter prevalence, dumpster and waste bin locations and trash sorting effectiveness were all investigated. First, we found that the majority of the campus had small amounts of litter. Our team found 10 multi-colored trash bins and 9 dumpsters. The multi-colored bins are meant to separate waste, however, they often contain unseparated waste. The locations of bins and dumpsters were mapped as shown in Appendix C:

Figure 22.

During interviews with the manager and employees of the two campus mess halls, we determined that 300 kg of food is wasted between both mess halls. A bar graph of the mess hall waste can be seen in Figure 6.

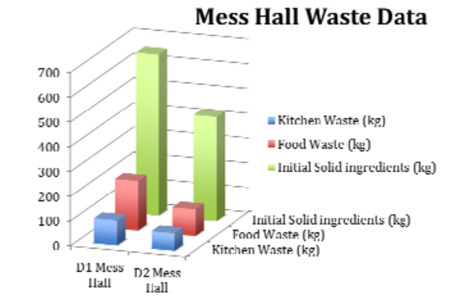

Figure 6: Waste generated from each mess hall on daily basis

Through an audit of the waste bins located in the B6 Student Hostel, we identified recyclables as the primary form of waste generated in student housing. A bar graph of our data can be seen in Figure 7.

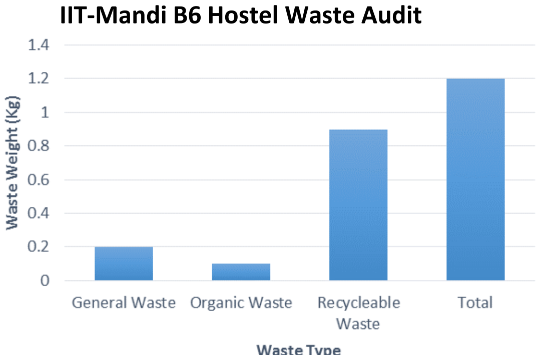

Figure 7: Results of B6 Hostel waste audit

Our team visited the local village of Kataula to evaluate the waste disposal practices of its residents. Solid waste pollution was more apparent in Kataula than on the IIT Campus. Moderate trash was found in gutters lining the road. The majority of inorganic waste appeared to be food packaging and empty drink containers. Large amounts of solid waste was dumped off a cliff along the river. Our team observed some burnt trash piles as well. Finally, we were unable to find public waste bins in Kataula. To understand the local waste composition, household waste was sampled over a two day period, the results are shown in Figure 8.

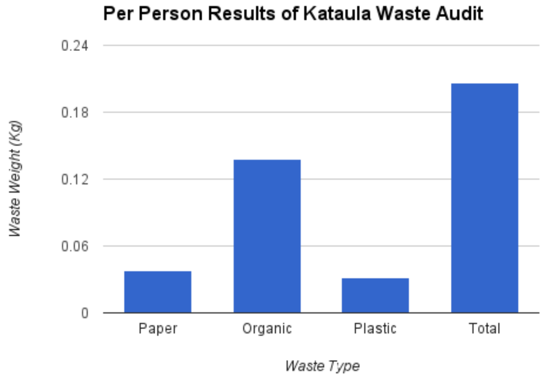

Figure 8: Waste generated per person per day in Kataula

After conducting a rapid site assessment, it became clear that Katindhi was much less polluted than Kataula. We observed some trash on the side of the road, however, trash did not line the entire street. Katindhi also lacked public waste bins. Unique to Katindhi, we found numerous piles of burnt trash; significantly more than what was observed in Kataula.

While conducting a site assessment in Navlay the team noticed a lack of solid waste pollution. We were able to locate a few small waste burning piles, but could not find a local dumping site. In addition, there were composting piles in almost every field but public waste bins were nonexistent.

Objective 2: Waste collection programs and infrastructure

This section describes the team's analysis of the current waste management systems and infrastructure on campus and in the surrounding villages. It is important to note that none of the villages have any sort of official collection or management system. In contrast the campus has a formalized system that is capable of handling the current population, but needs to be expanded to accommodate the incoming increased student count.

IIT campus

The IIT campus has a coordinated system of waste disposal which utilizes waste bins and dumpsters around campus to collect waste from campus residents and visitors. This waste is ultimately taken to Mandi's municipal landfill. Through our interviews with Colonel Naik, the campus superintendent, waste employees, and students, as well as our own observations, we developed a model that shows the waste flow on campus. This is described by the flow chart seen in Figure 9.

As can be seen in the flow chart, there is generally one condition that determines the flow of waste post disposal: the user's location. The location of the user on campus determines which type of waste bin is available. There are three main categories of waste bins on campus: indoor bins, multi-colored outdoor bins, and

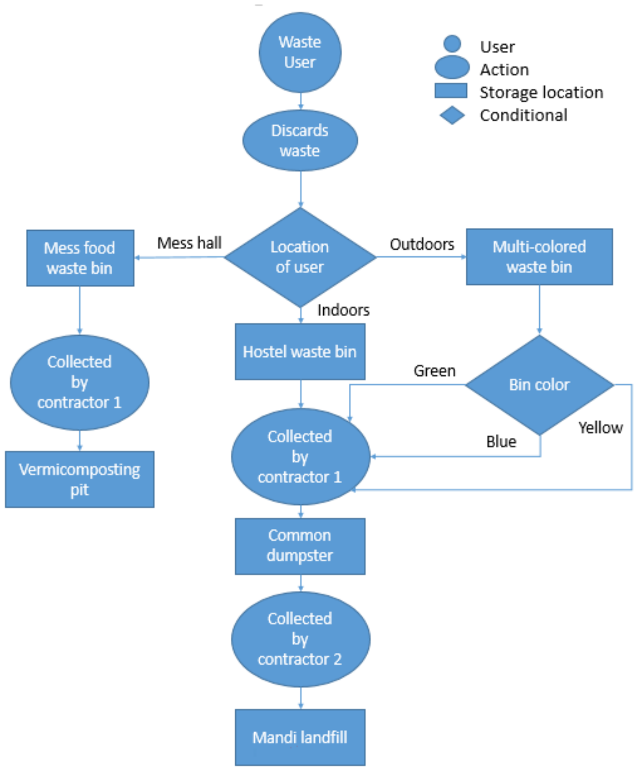

Figure 9: Flow chart of the waste flow on campus from the individual.

Figure 10: Multi-colored waste separation bins (left) unseparated indoor waste bin (middle), mess hall food waste bin (right)

mess hall bins for food waste. An example of each of these can be seen in Figure 10.

The multi- colored bins found on the campus grounds are meant to facilitate source separation of the waste. While color-coded, many of the bin labels have fallen off; this makes it difficult for users to separate waste. Furthermore, a contractor empties all bins into the communal dumpsters on a daily basis seen in Figure 11. This removes the environmental benefit from source separation.

Figure 11: Contractor depositing an indoor waste bin into a communal dumpster

Unlike the multi-colored bins, indoor waste bins are utilized to collect all forms of trash in the same bin. These bins are located in the hostels and academic buildings on campus. They are deposited each day in one of the communal dumpsters by the same contractor mentioned above. These dumpsters are ultimately picked up by a second contractor who takes them to the Mandi municipal landfill.

The mess hall bins have a different destination from the previous two bin types. At every mess hall meal, food waste is deposited into these bins. Once a day, this waste is deposited into a vermicomposting pit. This composting pit can be seen in Figure 12, on right. The compost

Figure 12: The vermicomposting pit for food waste on campus. It was constructed in Dec 2015.

created here will ultimately be used as fertilizer in the IIT-Mandi medical garden.

Villages

The waste management practices used in each village in the region are unique to that village; however, there are common themes that the team has identified. This has allowed us to create a flowchart of the common movement of waste within an average village in the area. This flowchart can be seen in Figure 13.

From interviews and observations, our team determined three common waste disposal habits: burning, unregulated dumping or tossing, and composting. The prevalence of each of these methods can be seen in Figure 14. Kataula seemed to be the most polluted village, and 54% of locals reported dumping as their primary

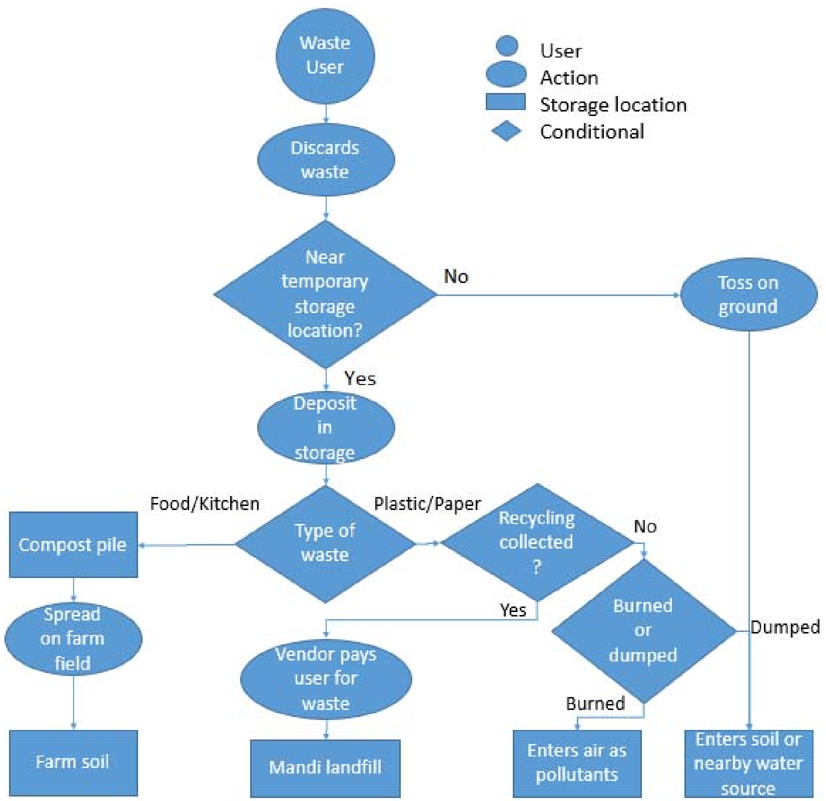

Figure 13: Flowchart of the waste movement within an average village of the Mandi district

method of waste disposal. Katindhi was significantly less polluted than Kataula. In Katindhi, 63% of locals reported burning waste as their primary method of disposal. Many of the shop owners informed us that locals sell glass and certain plastics to recycling vendors once a month. Navlay, showed the least amount of solid waste pollution; according to locals, the majority of waste is either burned or composted.

Objective 3: Gauging perceptions and preferences

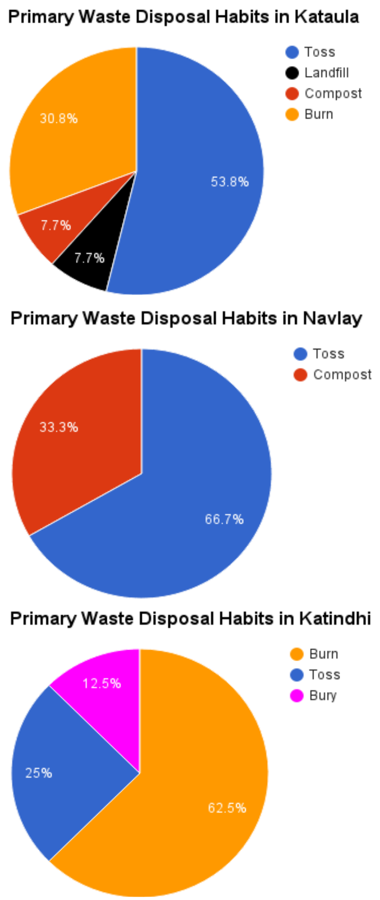

Figure 14: Pie charts of villager waste disposal practices

IIT Campus

The team spent several days evaluating the waste disposal habits of IIT students. We determined that most students understand the purpose of having multicolored waste bins. However, as shown in Figure 15, only 27.8% of students consistently separate their waste. The students were asked why they neglected to follow the separation system. The most common answer was that inadequate labeling made it difficult to determine the appropriate bin to use. This coincides with the fact that 78% of students do not know which type of waste goes in which colored bin.

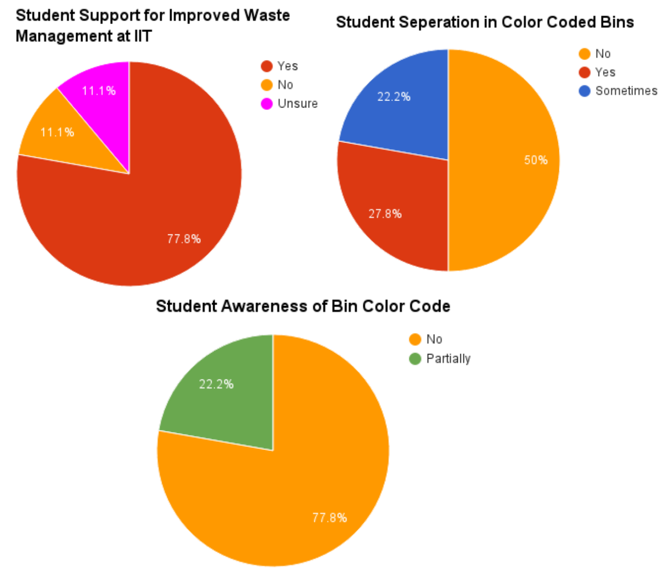

Figure 15 Pie charts of student interview responses

The team also evaluated the perceptions of IIT students with regards to the current waste management system on campus. Seventy eight percent of students recognized that the current system needs to be improved (see Figure 15), however, the responses varied with regards to the root of the problem. Some students blamed their colleagues for not separating waste upon disposal, while others blamed the institution for not implementing an effective system.

Villages

To identify the amount of local support waste management change, villagers were asked about their desire for improvements. The majority of villagers interviewed displayed a disinterest or opposition to any change being made to the current informal system. As shown in Figure 16, Kataula was the only village where locals consistently seemed receptive to implementing a better waste management system.

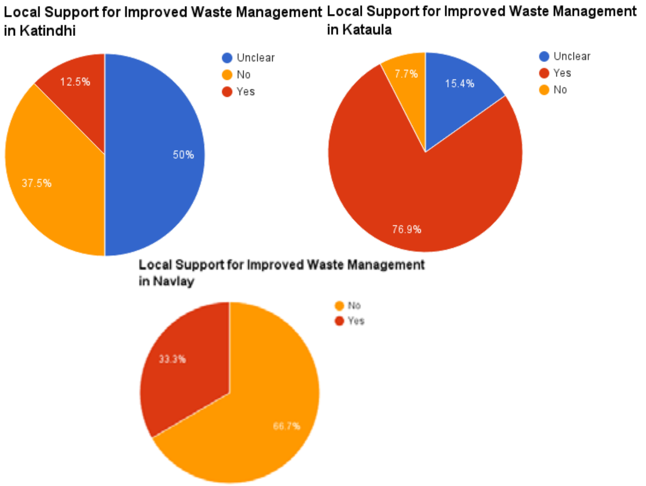

Figure 16: Pie charts of villager support for changes to status quo

Figure 17: Diagram of SWOT analysis for the waste management system on the IIT-Mandi campus.

Discussion

IIT Campus Discussion

The team's findings for the IIT-Mandi campus were used to conduct a SWOT analysis, shown in Figure 17. This analysis is focused on the capacity of the campuses existing system to handle waste. As shown in this analysis, the campus does a decent job of handling day-to-day waste with the vermicomposting of food waste being a particular strength. However, the success of waste separation on campus has been minimal at best. The campus residents do not separate their waste in the appropriate bins, and even when they do, that waste is mixed in the communal dumpsters before being taken to Mandi. Fortunately, students and faculty are receptive to change, so any incentives to improve the system should be able to garner the necessary support.

Villages Discussion

The team's findings in the local villages were used to conduct a SWOT analysis of the common systems as seen in Figure 18. This analysis focuses on the villages' ability to handle waste in an environmentally sustainable manner. As shown in the analysis, the villages primarily struggle with the handling of plastics and packaging. Most organic waste, which makes up the majority of waste in villages, is composted regularly. Unfortunately, the other forms of waste are either burned or dumped in unregulated sites. Although this removes them from sight in most situations, it fails to address environmental and health concerns. The villagers are often either not aware or not concerned with these effects. This means apathy or a lack of awareness is a threat to any future waste system. Fortunately, Kataula in particular seemed receptive to change and would be a good starting location to test an improved system.

Figure 18: Diagram of the SWOT analysis for the waste systems found in the local villages

Project Outcomes

In this section a number of suggestions are presented to improve on some of the primary weak points found within the waste management systems of the IIT-Mandi campus and the village of Kataula.

Recommendations for the IIT-Mandi campus

The team analyzed the IIT-Mandi waste management system using a SWOT analysis and identified waste separation as a major area of weakness. The influx of students from the opening of the North campus in August 2016 also posed a major threat to the current system. To address these and other concerns we developed suggestion packet called the "IIT-Mandi Solid Waste Management Improvement Guide 2016". This guide outlines a timeline for improving waste management on campus. The full packet can be found in Supplemental Materials.

Part of this plan required that the campus update their existing separation bins with new engineered lids and permanent labels. These lids would limit the types of waste that can be easily discarded in a bin. According to Duffy (2009) such a system can increase plastic bottle recycling by over 30%. The team created prototypes of these improvements. These can be seen in Figure 19. These prototypes were tested over a three day period. Each day the contents of each a bin was evaluated for accuracy. As shown in Figure 20, there was an average of 11% improvement in separation. Unfortunately, the food waste bin saw a 9% drop in correct contents.

Figure 19: A set of separation bins that were fitted with the teams lid and label prototypes.

However, this could be due to the limited sample size available from that bin which was nearly

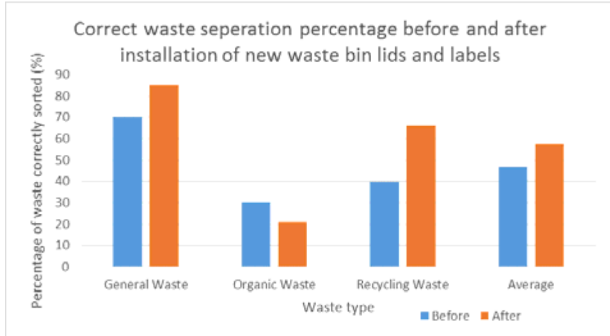

Figure 20: The percentage of correct waste in each separation bin averaged over three days before and after prototype installation.

empty on all three days. Still, the overall success of the prototypes suggests the campus should pursue such improvements further.

To keep the waste separated in communal dumpsters, we also created SolidWorks models of dumpster dividers. One such model can be seen in Figure 21.

Additional suggestions in the plan included the creation of informative posters and expansion of the current campus Earth day event. Prototypes of informative poster designs were included in the plan and can be found in Supplemental Materials.

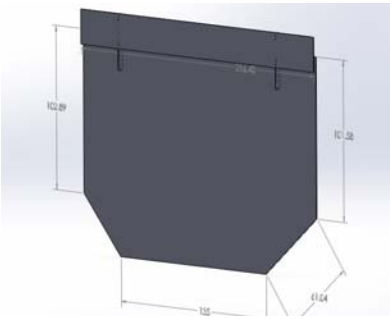

Figure 21: Dumpster divider design for the large communal dumpsters

Recommendations for Kataula

After conducting a thorough analysis of Kataula's current waste management practices, our team identified two major problems: a lack of public awareness with regards to solid waste pollution and inadequate waste management infrastructure. In an effort to combat these problems, our team developed both an educational guide and an infrastructure improvement packet. Both of these can be seen in Supplemental Materials.

To improve local awareness, the team decided to utilize the influence of the primary school. We created an education packet which contained suggestions for environmental curriculums, waste management project ideas, proper practices the school can follow, and suggestions for the implementation of an earth day similar to the IIT's. The guide was presented to the school principal who expressed approval of the ideas. With these ideas implemented, an environmental consciousness will begin to spread into the community through their children.

To capitalize on increasing environmental awareness, Kataula will need to create a more formalized waste management system. To assist in this effort we created a packet of suggestions. One major suggestion is the collection of recyclables by a third party. The local hospital which plans to soon triple its patient capacity has employed a recycling contractor to collect their recyclable waste on a regular basis. This contractor will begin collection in two months. The town can utilize this system by having shop owners save their recyclables until the contractor's regular visits.

We interviewed 7 local shop owners about this idea and found 71% willing to save recyclables. Of these 20% said they would do it only with payment from the contractor similar to the system used in Katindhi. Many of the shop owners would also prefer dust bins be provided to them or communal dumpsters be used for storing recyclables. These hurdles are fortunately not insurmountable and the high percentage of participation means such a system could be implemented effectively.

Conclusions

After analyzing waste management at the IIT campus and three villages, our team was able to collect various forms of data. We collected waste metrics, assessed waste management infrastructure, gauged common waste disposal practices, and determined local perceptions regarding change. Through our research, we determined that the IIT and the three villages need to improve both solid waste management infrastructure and environmental awareness. Finally, we presented both the IIT campus and the village of Kataula with a set of actionable recommendations to improve the current waste management systems.

The full report and supplemental Materials for this project can be found at:

http://www.wpi.edu/E-project-db/E-project-search/search, *using key words from the project title.*

Outcomes delivered after May 1 will appear on the IIT's ISTP page at:

http://www.iitmandi.ac.in/istp/projects.html

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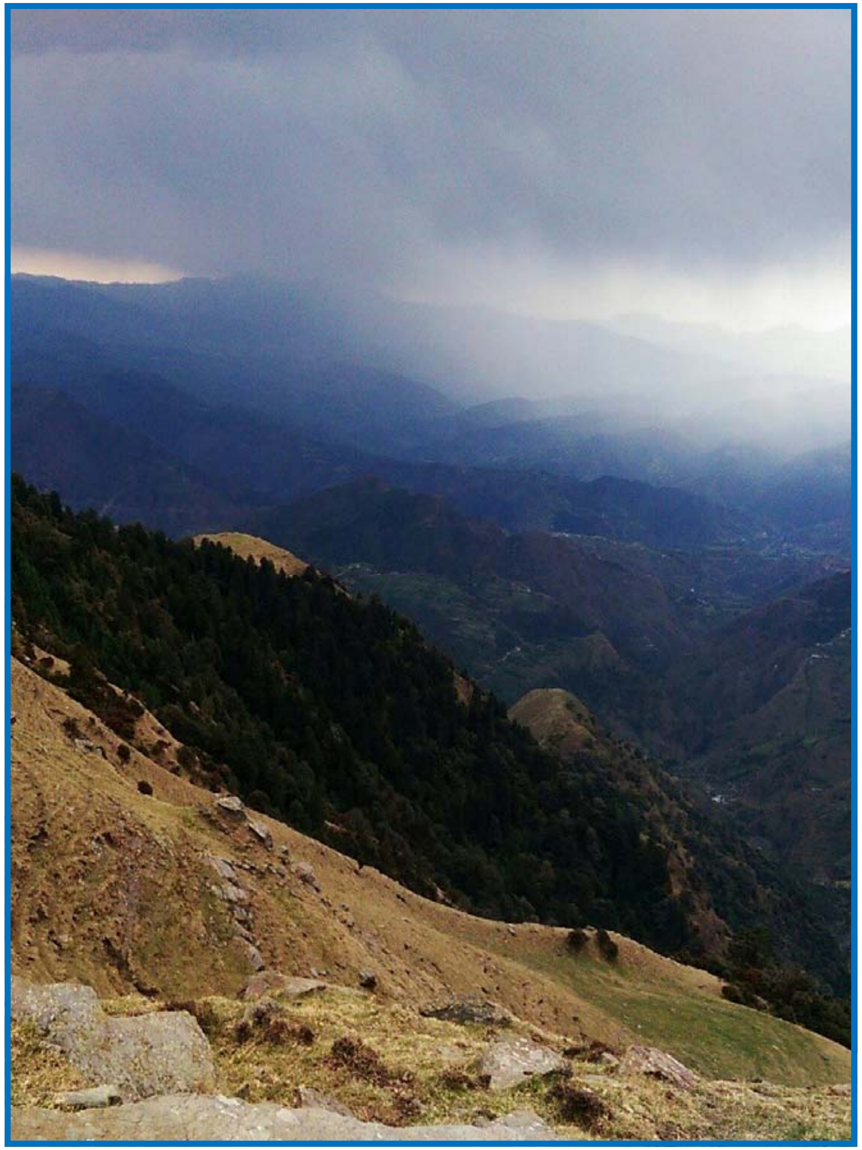
An Opportunity for Rainwater Harvesting



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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An Interactive Qualifying Project/Interdisciplinary Sociotechnical Project submitted to: WPI

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 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).

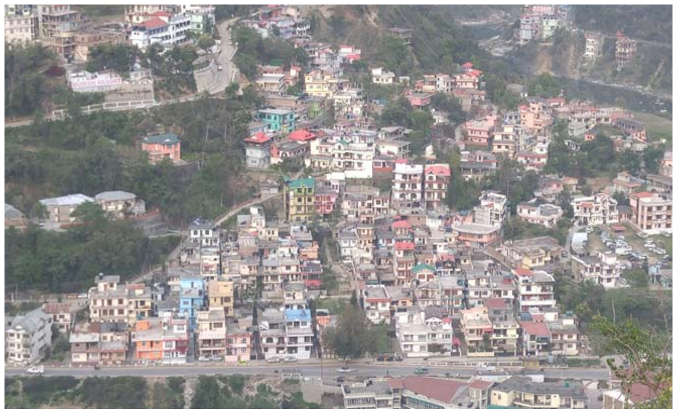

Figure 1 - Bhiuli, an area facing water scarcity in Mandi, Himachal Pradesh

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). 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.

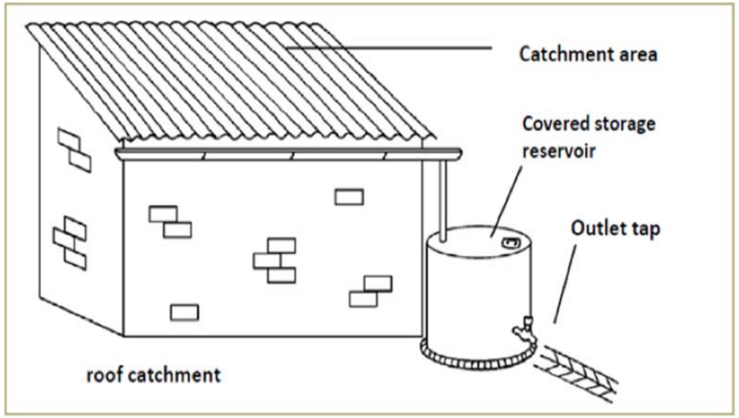

Figure 2: Roof capture system (UNEP, 1997)

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. 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).

Figure 3: Rooftop Water Storage Tanks in Mandi Town (Photo: J. Agresta)

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).

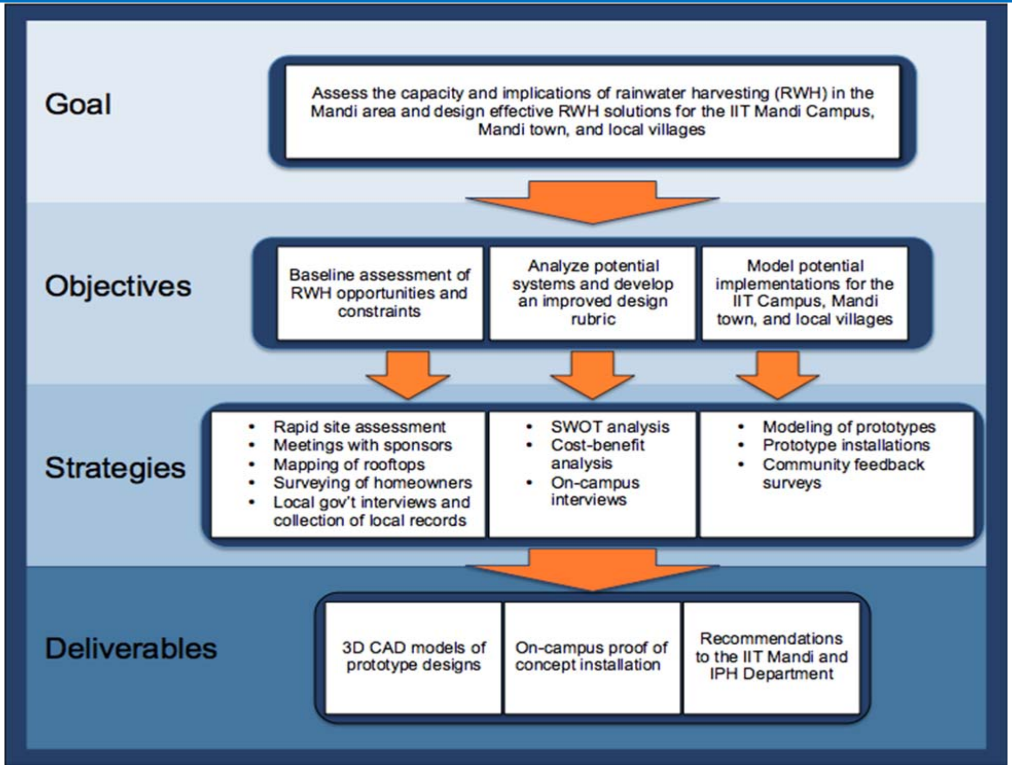

Figure 4: Project Overview

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

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 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).

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.

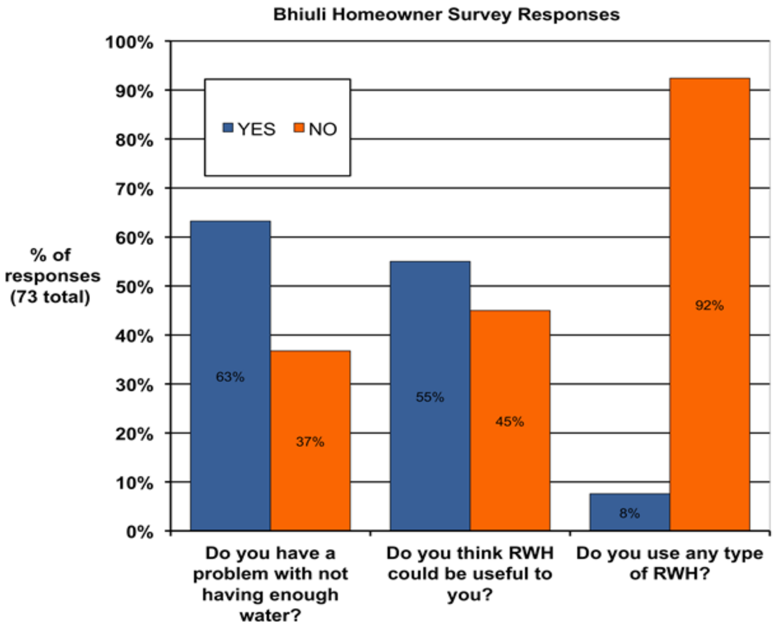

Figure 5: Homeowner survey responses

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).

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

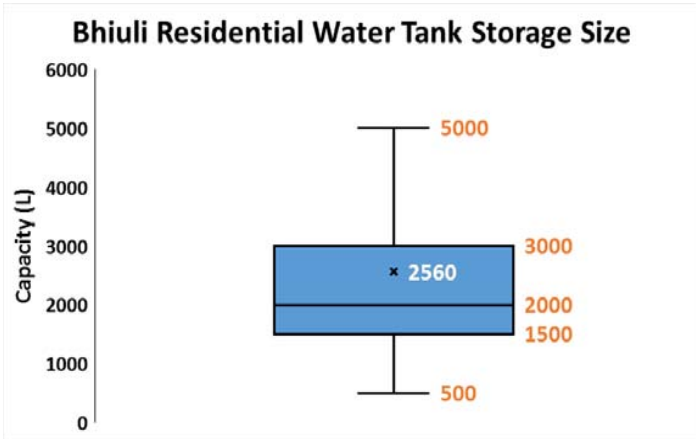

Figure 6: Water storage capacity based on survey results

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 then 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, illustrates potential by building.

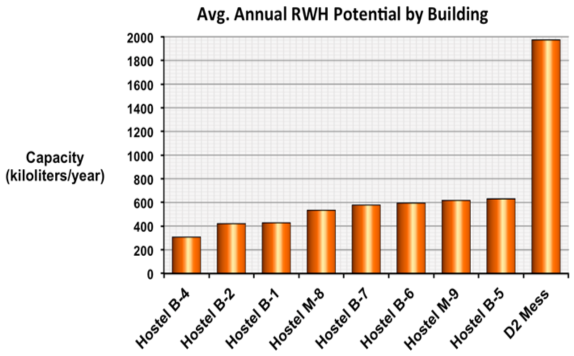

Figure 7: IIT Campus RWH potential of selected buildings

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

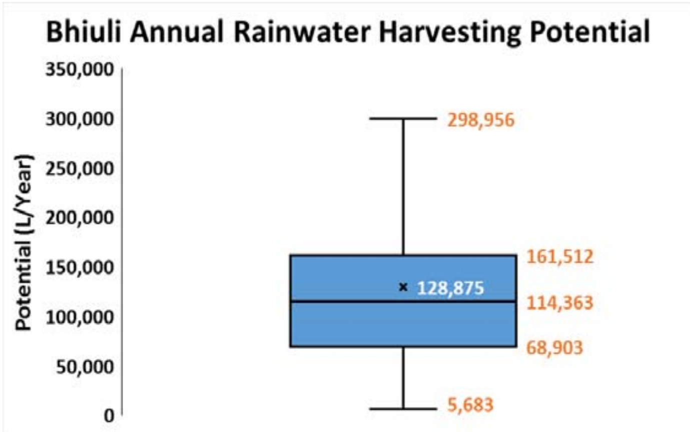

Figure 8: Distribution of annual RWH potential of rooftops in Bhiuli

of producing between 68,903 and 161,512 liters of harvested rainwater per year.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 (Figure 9).

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.

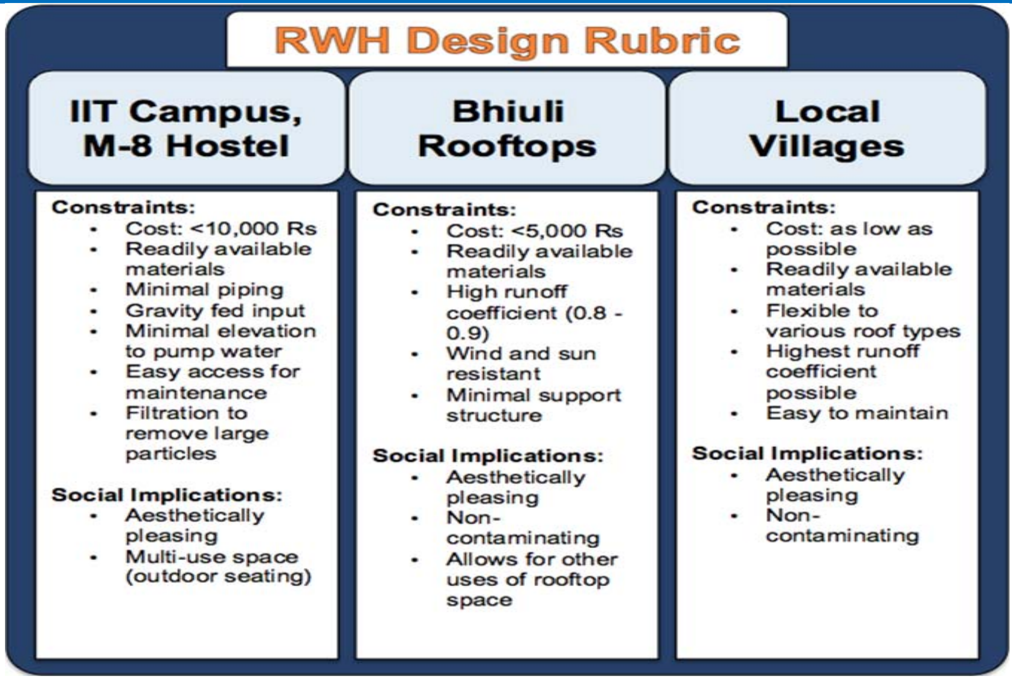

Figure 9: Design rubric of 3 possible implementations

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 on-campus 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).

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.

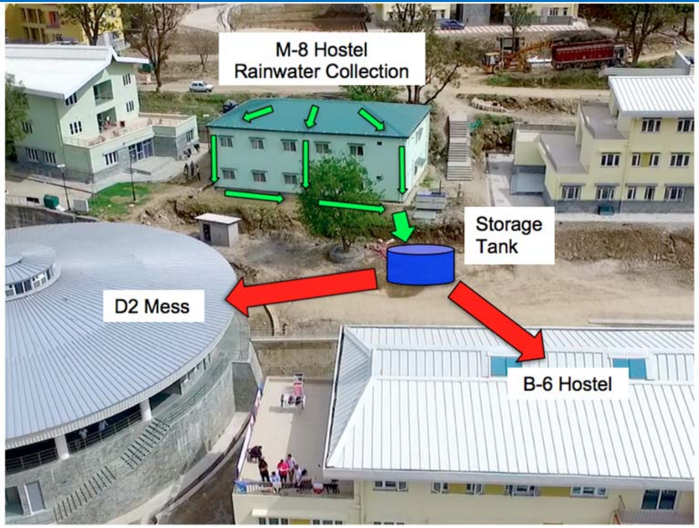

Figure 10: Immediate campus implementation

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). 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

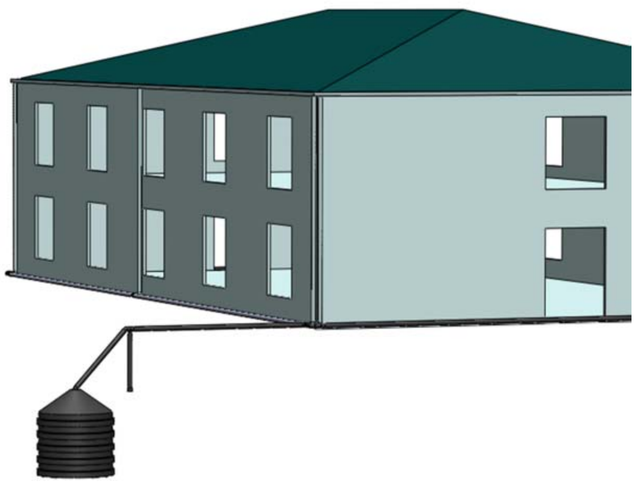

Figure 11: A CAD model of the initial prototype system

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.

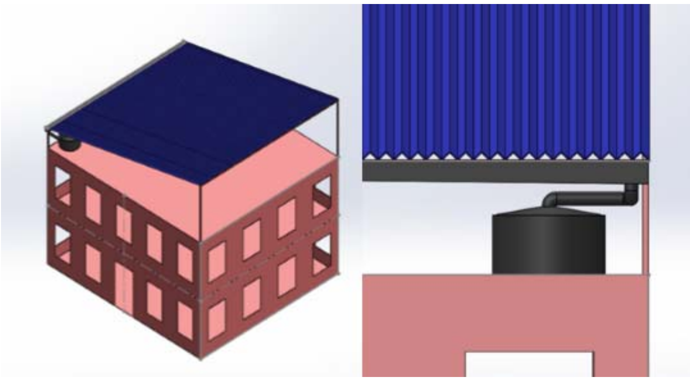

Figure 12: Mandi town model

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). Water then flows down the path of the chain and the bottles act as a splash guard 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

Figure 13: Village solution

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 large-scale 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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- Dr. Stephen McCauley
- Dr. Ingrid Shockey

The full report and supplemental materials for this project can be found at http://www.wpi.edu/E-project-db/E-project-search/search using keywords from the project title. Additional ISTPs can be found at http://www.iitmandi.ac.in/istp/projects.html.

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Developing Smart Origami Shelters for Himachal Pradesh

Abstract

This project applied the principles of origami to develop smart shelters that can be adapted for individuals or groups in Himachal Pradesh, India. We engaged diverse user groups, including slum residents, migratory construction workers, and trekkers in the design process to develop a versatile structure that is portable, deployable, and weather resistant. The final product was field-tested among those same user groups to produce a list of additional features and changes to make in future versions.

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An Interactive Qualifying Project/Interdisciplinary Sociotechnical Project submitted to:

The case for better semi-permanent shelters in Himachal Pradesh

In 2015, a team of students undertook a design challenge to create a folding, lightweight temporary shelter suited towards the needs of a variety of stakeholders in and around Himachal Pradesh. The resulting cardboard and tarp prototype could fold flat for transport and expand dynamically to house up to two individuals. The use of cardboard however, while not unusual, was not ideal for long-term usage. In order to advance the idea, we engaged the users in the design process, explored better materials, and created and field-tested an improved prototype.

After feedback and field studies, the team determined that a majority of the target audience was looking for semi-permanent shelters rather than portable and lightweight structures (see Figure 1). In order to improve upon the existing structures used by stakeholders, the team solicited a range of requirements that the design

Figure 1: Current shelters of homeless population in Himachal Pradesh.

should meet. The final shelter should withstand heavy rainfall, high winds, and snow accumulation. Additionally, it should have insulating properties, be fire resistant, and support for some form of lighting. These extra qualities reduce portability and increase cost, but also increase comfort during extended use. All of these features were combined into a structure that is compact when stored and can be rapidly deployed when needed.

The goal of this project was to manufacture an origami shelter that meets stakeholder requirements and features 'smart' technologies. To meet that goal, we identified four objectives:

1. Identify materials and manufacturing options for production
2. Engage in user-based design in collaboration with stakeholders
3. Produce 3 final products based on 1 initial prototype that meet the design criteria
4. Distribute prototypes to users to perform field-testing and gather feedback

Origami as a design foundation

The Japanese art of origami has been in practice since 105 CE (History of Origami, 2015). After studying the techniques and applications associated with origami, researchers and designers have incorporated these unique features into large-scale deployable structures. As the practice of folding techniques advanced, so has the scope of the feasible applications; today, these techniques are being used to improve cutting edge technologies including NASA satellites, robotics, airbags, heart stents, and retinal implants (Main, 2014). The use of origami principles in these advanced fields indicates its versatility as a viable construction technique for shelters (Rihal, 2013).

The basic folds of origami most often used in disaster relief shelters today include the Miura-Ori pattern, Yoshimura/diamond pattern, and the reverse fold (see Figure 2). Rihal chose the reverse fold and Yoshimura fold were due to their qualities of “significant lateral strength and

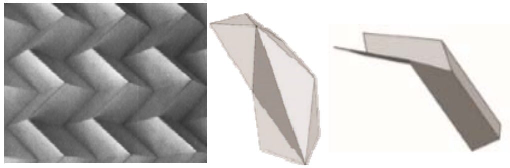


Figure 2: Miura fold, Yoshimura fold, reverse fold, and overlap style joints (Gattas & You 2016; Rihal, 2013).

stiffness in the longitudinal direction” (Rihal, 2013, p. 1086). Another important property of origami folds is deployability – the ability to quickly assemble on site and collapse for transport. From this perspective, the Miura-Ori fold is one of the best types of folds as it is easily able to compress into squares via orthogonal folding (Miura, 1994). Miura, the originator of the Miura-Ora pattern, explains in his 1994 work that this property is what makes the fold so deployable. This factor is why NASA has used the Miura-Ora fold in transporting satellites and why we felt it was appropriate for a compact semi-permanent shelters (Miura, 1994).

In terms of offering flexibility in modular unit expansion, the two simplest types of joints for connecting origami pieces are the overlap joint and the seam joint. The overlap joint provides the most strength and stiffness as the material itself provides the necessary support (see

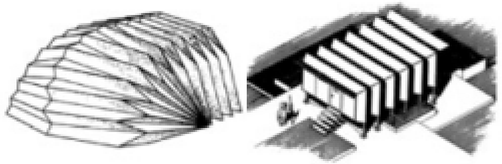
Figure 3: Overlap joint shown on a Yoshimura pat-

Figure 3) (Rihal, 2013). The seam joint simply connects two structures along a seam without overlap by adding additional material such as tape or fabric. The advantage of the seam joint is that it minimizes material waste and is more flexible than the overlap joint.

Materials and assembly in shelter design

To identify appropriate materials, we analyzed those most commonly used in existing semi-permanent shelters as well as other materials that meet design requirements but are not typically used in existing shelters. Material properties were taken from various materials databases, including CES EduPack 2015 (see Table 1 of Appendix A, Supplemental Materials).

There are, in general, three types of non-origami or simple origami shelters: soft-walled, clamshell, and rigid-walled accordion style (see Figure 4). Soft-walled shelters tend to be more adaptable and can be more easily compacted, but lack the rigidity necessary to be self-supporting (Thrall & Quaglia, 2014). This makes rigid-walled structures more suited towards permanent or semi-permanent housing and soft-walled structures more suited towards temporary shelters. Although origami can create complex structures, doing so with thicker materials becomes difficult because as the origami folding pattern increases in complexity the opportuni-



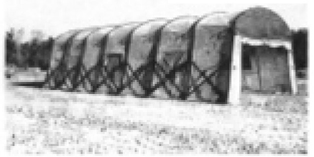


Figure 4: Clamshell, rigid-walled accordion, and soft-walled accordion style shelters (Thrall &

ties for misalignments increases. For this reason, simple folding techniques, such as the reverse fold, are best suited for this project. Two good examples of origami style shelters that use simple folding techniques are the Biodegradable

Figure 5: Biodegradable Tent (left) and KarTent (right) (Harden, 2015; KarTent, 2015).

Tent and the KarTent (see Figure 5). These shelters are designed for limited use by one or two individuals and are therefore not suited for extended use by families or other large groups. The key benefits of an origami shelter are deployability and rigidity, but these advantages do not scale well as the rigidity of a large scale origami shelter increases its weight and reduces the packing efficiency.

Site-specific considerations

In response to origami's complexity, simple tent structures were initially explored to understand their limitations in the design chal-

Figure 6: Double-walled tent, A-frame, tarp tent

lenge. Tents can be highly compact and lightweight (see Figure 6), and have the advantages of being highly portable, lightweight, and scalable. On a limited basis, for one or two individuals, tents are lighter and more compact than an equivalently sized origami shelter. Additionally, tents are soft-walled structures, which make them more flexible and thus less prone to failure. However, we determined that they rely on expensive and highly specialized materials that are neither available nor affordable in Himachal Pradesh (Haist & Neale, 2015).

In Himachal Pradesh, there are specific user groups that require portable or improved housing. For example, Gaddi Herders, trekkers, and urban homeless require highly portable lightweight shelters (Andrews, Felix, Joshi, Mehta & Novinyo, 2015). Slum residents require more permanent housing, which meets building permits, is heavier, and has additional features for day-to-day living. Although all of the potential users required some form of improved shelter, none of their requirements were perfectly matched with the benefits provided by an origami shelter. As discussed above, on a small scale, tents are lighter and more compact than origami shelters and thus are better suited to the needs of herders, trekkers, and the urban homeless. For more permanent residents, there is less need for rapid deployability and thus an origami shelter is a good, but not ideal, solution for this group of users.

Increasing functionality for extended use

In addition to meeting the basic requirements of the stakeholders, incorporating additional 'smart' technologies and adaptations that increase the quality of life of a user was a priority. Some of these technologies have been implemented in currently available shelters and thus it is important to review those implementations.

Solar technology has long been added to tents in order to accommodate everything from recharging cellphones to powering refrigerators and generators. One example, the Cinch Tent uses solar panels attached to the roof to power recharging for devices and LED stakes and lanterns for convenience at night (Weiss, 2015).

Figure 7: The Cinch tent (left) and the Kaleidoscope tent (right) (Weiss, 2015; Solar Powered

Other tents, such as the Kaleidoscope Tent (see in Figure 7) use solar fabric to create solar panels that bend with the shape of the tent (Solar Powered Tents, 2016).

With the addition of solar panels comes an ability to light the interior space at night. Recently developed to fill this need without high expense was the charity Liter of Light, which uses plastic bottles filled with bleach and water to refract both sunlight and the light of LEDs into the shelter (see Figure 8). When attached to a

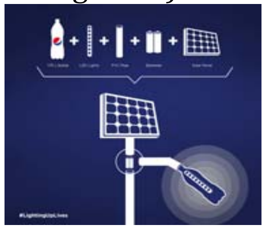


Figure 8: Liter of Light with solar panel (Zee,

solar panel and sensor, this system can utilize sunlight during the day and the light of the LEDs at night. Simply installed in a hole cut into the ceiling, a one-liter bottle can light a 15 square-meter room at night. These lights last upwards of five years before the water needs to be replaced, while the LEDs have a lifespan of 70,000 hours (Williams, 2015).

Another feature that would be useful is the ability to collect water for drinking and other uses. This has been accomplished in two main ways for shelters: rooftop rainwater collection and solar stills. Basic catchment systems, such as tarps and plastic funnels, have been employed to catch rainwater on tents; these systems allow the majority of this water to be collected and stored for drinking or other purposes. One such method can be seen used in the Kammok Rain Tarp (see Figure 9). The Kammok tarp uses the

Figure 9: The Kammok rain tarp (left) and water collection system (right) (Weiss, 2013)

natural curve of its shape as a catchment for rain water, which it then funnels into a holding canister (Weiss, 2013)

For use during the dry season, a solar still can be added to the shelter. Solar stills are a method of water collection often used when there is not an abundance of rain. Based on the design of stills taught in the outdoor survival training used by the US Air Force, this still would be both simple and effective (Jones, 2016).

A final addition for long-term use of this shelter is an integrated storage system which makes use of space that would otherwise be lost due to the origami folds used in the shelter's construction. Based on similar principles to freestanding organizers built by Coleman, incorporating a flexible structure that compacts and expands with the shelter while utilizing the rigidity of the shelter as a frame (see Figure 10), would be ideal.

Figure 10: Coleman freestanding organizer (The Coleman Company).

In creating an optimal solution for a semi-permanent origami shelter, it is apparent that such a design should use simple folding techniques, feature a combination of materials to meet all desired requirements, use one or both of the simple joints to provide maximum support and flexibility, and incorporate multiple 'smart' features. A shelter that incorporates all of these features will not only meet stakeholder requirements but will also be able to efficiently manufactured.

Methodology: Creating shelters for users in Himachal Pradesh

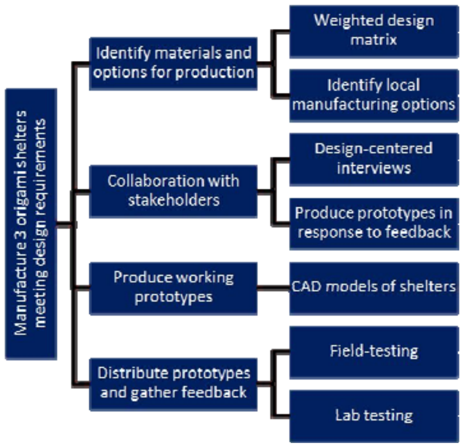


Figure 11: Methodological approach to the project

Objective 1: Identify materials and manufacturing options for production

We interviewed IIT-Mandi faculty experts in material science in order to identify a suitable materials database to use in order to select the materials that best fit the design requirements and were locally available. From there, materials were added to a weighted design matrix, and the materials which best fit the project were chosen. We also identified local manufacturing options, with a focus on cottage industry and personal manufacturing (see Appendix B, Supplemental Materials).

Objective 2: Engage in user-based design in collaboration with stakeholders

We revisited and completed the assessments of shelters from stakeholders initiated in a study from 2015. We conducted additional design-centered interviews and observations with groups of stakeholders; initially targeting potential users near Victoria Bridge and the IIT campus in Kamand. These interviews and observations were documented through handwritten and photographic records. This method engaged the users immediately through early direct contact, which was shown to be more effective than simply using them as design verification.

Objective 3: Produce 3 final products based on 1 initial prototype that meet design criteria

As part of the design and production of the shelter the team used SolidWorks to create a selection of potential designs; from that pool the best design was chosen for full-scale manufacturing. To compensate for having raw materials that were not necessarily as large as required, the team used a modular approach by connecting several pieces together with seam and overlap joints. Overall, the team sought to develop a total of four models: an initial prototype for field-testing followed by three final products with modifications based on feedback from testing.

Objective 4: Distribute prototypes to users to perform field testing and gather feedback

Field testing was performed in two parts: by bringing the prototype to users, and by performing laboratory testing to verify design specifications. We solicited a range of volunteers from both Mandi and Kamand, as well as from interested IIT and WPI students for field-testing of full-scale prototypes. Feedback from the field-testing was collected via interviews conducted by team members (see Appendix D, Supplemental Materials).

Results

The results of this project are presented below divided by objective. Overall the results focus on identifying appropriate stakeholders, creation of physical and mathematical shelter models in response to stakeholder needs, and validating those models through field and lab testing.

Objective 1: Materials and manufacturing

Identifying an appropriate material was accomplished by completing the design matrix (see Appendix B in Supplemental Materials) described in the methodology. Corriboard, which is a form of corrugated plastic sheeting, was identified as the optimal material. The key properties that made corriboard the optimal material were that it was waterproof, lightweight, and rigid. Part of the initial shelter assessments involved determining how they manufactured their current shelters. The majority of potential users built their own shelters with simple hand tools. To allow users to manufacture, install, and maintain the origami shelters, we decided to build our origami shelter in the similar manner.

Objective 2: User-based design

In total, the team conducted interviews and assessments with four stakeholder sets: slum residents, urban homeless, street vendors, and one of the advisors for the IIT-Mandi trekking club. We used standard interview format with most stakeholders, and an unstructured interview for the trekking club advisor.

Figure 12 summarizes the shelter needs of the potential stakeholders and maps those needs to the benefits of an origami shelter. The street vendors, for example, reported not needing a shelter as they rent apartments for 2-3 months

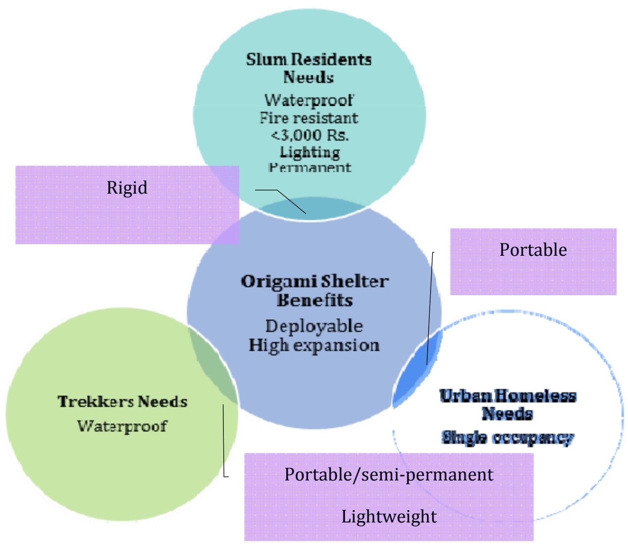


Figure 12: Mapping of the benefits of an origami shelter to the needs of each potential stakeholder group.

in each town they travel to, and thus were not included in the figure. As indicated in Figure 12, an origami shelter would most benefit those with a need for a semi-permanent or highly portable shelter.

Although not all of the user groups proved to be well-suited to an origami shelter, they all provided valuable information on what could be potentially beneficial for a semi-permanent shelter. For example, Figure 13 shows the number of occupants per shelter, indicating that up to 6 people frequently reside in a relatively small shelter.

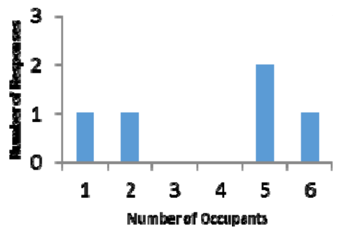


Figure 13: Histogram of the number of occupants per shelter

Figure 14 indicates that the two most popular activities performed in the shelter are cooking and sleeping. From this information, it was decided that the origami shelter must be large enough to accommodate multiple beds, an area for food preparation, and be fire resistant.

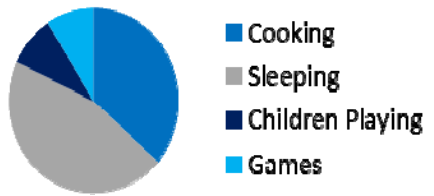


Figure 14: Popularity of activities conducted in the shelter

These findings indicated that semi-permanent shelters were the most appropriate match for origami structure applications. The target audience of a semi-permanent shelter includes, but is not limited to, trekking companies, roadside vendors, migratory construction workers, and special event organizers.

Objective 3: Produce 3 final shelters

We created computer aided design (CAD) models to explore different designs (see Figure 15). The model in Figure 15a was chosen as the

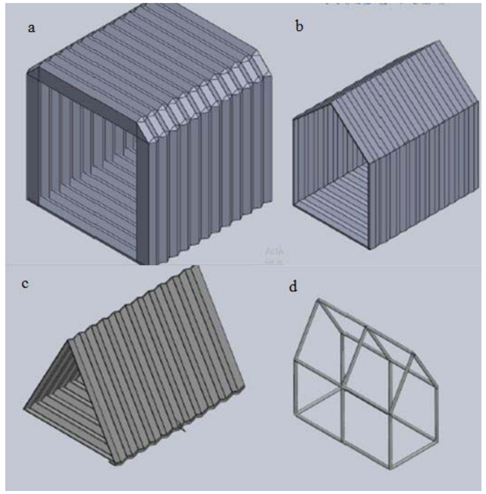


Figure 15: The isometric views of four of the initial shelter designs. (a) is a simple rectangle (b) is a simple pentagon (c) is an A-frame style shelter. (d) is an a pole-based alternative to an origami structure

best design for initial prototyping as it had the capability to be closed on both ends, had a large amount of usable interior space, and included only simple reverse folds and seam joints. Moving forward, the only change to that design was to make one of the sides shorter so that the roof

The CAD model was used to generate a mathematical model of the shelter design which took the material properties and basic shelter dimensions as inputs and calculated interior volume, dynamic heights, dynamic floor area, weight, dynamic length, percent elongation, and floor width based on the joint angle (see Figure 16).

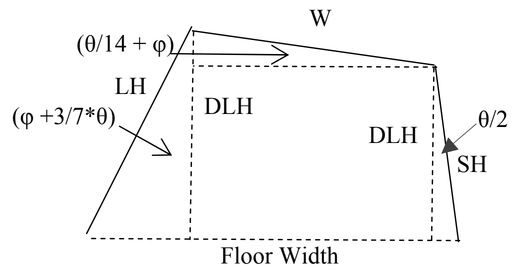


Figure 16: Sketch of interior cross-sectional area of shelter for mathematical model. LH is the long height, SH is the short height, and W is the width as measured on the flat panel before folding. θ is the joint angle, the angle between two panels and φ is the desired roof angle. DLH and DSH are the dynamic heights.

This model was used to optimize the shelter parameters so that the final shelter was adequately sized for an average person to stand in while maximizing usable interior space and minimizing both cost and weight. The model assumed that for every degree the joint angle increased, the roof angle decreased by 1/14 of a degree, the short side angle with the roof increased by ½ of a degree, and the long side angle with the roof increased by 3/7 of a degree. Ultimately, interior volume was chosen as the property to optimize and thus the parameters were adjusted to find the maximum interior volume while maintaining standing height on the longer of the two sides (see Figure 17). The maximum volume was achieved at an angle of 135˚ but this did not allow for standing height so the minimum acceptable volume, found at 45˚, was used to create the first prototype.

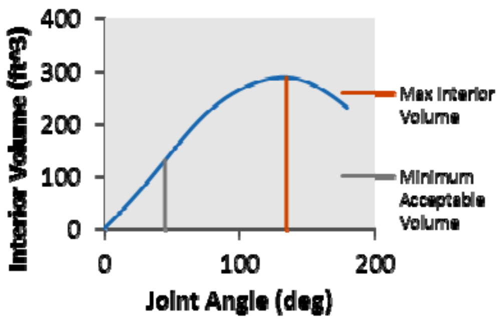


Figure 17: Interior volume graphed as a function of joint angle.

At the minimum acceptable interior volume, all model parameters were calculated to determine the dimensions and necessary angles for folding the corriboard sheets to create a full-scale model (see Table 1). These parameters were calculated for a model with 18 eight inch panels, LH=7', SH=5'5", w=3'3", thickness of 1/8", and a density of 4.68 kg/ft^3.

An initial prototype was constructed out of six sheets of corriboard connected with both overlap and seam joints (see Figure 18). The seam joints were sealed with tarp and the overlap joints were connected with PVC cement and bolts.

This prototype also included additional features that users identified as beneficial such as an integrated floor, windows, ventilation, and the ability to close on one side. While this prototype was the full height of the final design, it was 1/3 of the length of the final design as cost was an important consideration. This version was created for about 3,000 Rs.

Table 1: Model parameters calculated when the minimum acceptable volume is achieved

Parameters at Minimum Acceptable Volume	
Joint Angle (deg)	45
Roof Angle (deg)	19
Interior Volume (ft^3)	130
Dynamic Long Height (ft)	5.5
Dynamic Short Height (ft)	5
Dynamic Length (ft)	4.6
Dynamic Floor Area (ft^2)	47
Weight (kg)	14
Weight/Area (kg/ft^2)	0.29
Elongation (%)	2449
Floor Width (ft)	9.5

Figure 18: An isometric view of the initial prototype (top), collapsed shelter (bottom)

The final prototype was constructed of 14 sheets of corriboard connected with both seam and overlap joints (see Figure 19). Hinges were added along the short side and roof to increase compactness. Additionally, it included 'smart' features such as an integrated floor, rain water collection, solar lighting, internal storages, and in length, 6ft in height, and 5ft in width. With all these additional features, this version was created at a cost of about 10,000 Rs.

Figure 19: Isometric view of final prototype (top), collapsed shelter (bottom)

Although the initial goal of this project was to create three final shelters, upon completion of the initial prototype and the first final shelter the team decided to reduce this number from three shelters to a single shelter. The primary reasons for this decision were based on the cost of producing additional shelters and the time it would take to manufacture them. Despite allowing for simultaneous field-testing, creating additional shelters would result in a diminished ability to perform extensive field-testing in the time allotted.

Objective 4: Field-testing

Experimental Design Validation

Laboratory testing was employed to verify material properties and specific shelter design requirements including fire resistance, fatigue resistance through both folding and creep, and water resistance. During the flame test, cardboard was the only material to ignite; corriboard melted slightly in similar conditions, but only when exposed to direct flame. A foil and tape covering only marginally improved corriboard's fire resistance.

Fatigue resistance was tested for both folding and creep to ensure the shelter could withstand repeated deployment and extended use. Figure 20 shows the results of the folding fatigue test; the corriboard did show any signs of failure after

Figure 20: Folding fatigue resistance results

1000 folds. The 1000 fold threshold was used to simulate a shelter life of 5 years with it deployed in 2 month increments each year and a safety factor of approximately 20. The creep fatigue test was used to determine corriboard's behavior over time when loaded and to examine the effects of folding on creep resistance. The weighted mountain folded piece performed nearly as well as the unweighted flat piece over an 8.5hr period; in all cases some creep was observed (see Figure 21).

Water resistance was tested in two parts: testing of the shelter prototype and laboratory testing of the corriboard itself. During the prototype water testing, neither the overlap joint nor the windows leaked at all, the seam joint showed

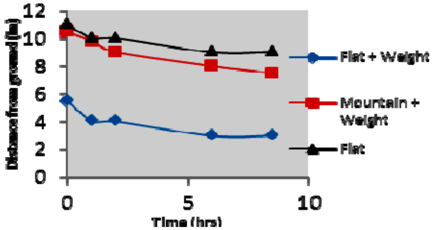


Figure 21: Graph of creep response for folded and unfolded corriboard

minimal leakage, and the shelter shed water efficiently (see Figure 22). The laboratory testing revealed that when exposed to water for 24 hours, the corriboard remained fully waterproof.

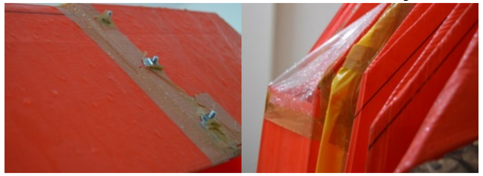


Figure 22: Water testing of shelter prototype.

Qualitative field-testing

The first shelter prototype was field-tested by ten volunteers: three construction workers and seven students. Three of the students participated in overnight field tests and the other four participated in the time trials described above. All volunteers were asked the same set of interview questions. Figure 23 shows all of the responses to the interview questions as fractions.

The temperature, compaction, and transportation questions show the most negative responses and the safety, space, and enclosure questions are the only questions with 100 percent agreement.

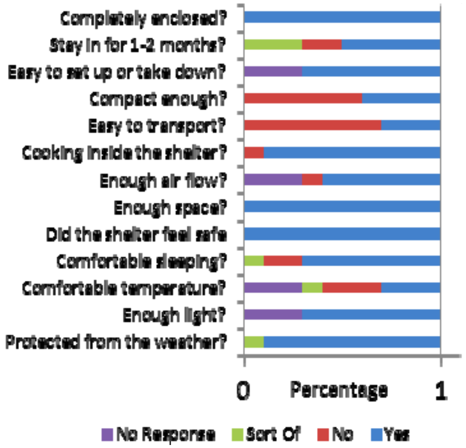


Figure 23: Field-testing feedback results for students and temporary construction worker

Once the final prototype was completed it too was field-tested with prospective users. The team met with and demonstrated the shelter to temporary construction workers, slum residents in Mandi, and roadside vendors (see Figure 24).

Figure 24: Meeting with slum residents during field-testing

The shelter was received with mixed positive feedback by the construction workers; 70% thought the shelter was innovative and potentially useful, while 30% thought the shelter need improvements in manufacturing to be useful. The primary areas of improvement involved making the shelter more wind and water resistance and improving the rigidity. All of the nearly 20 slum residents surveyed enthusiastically supported the shelter and felt its features completely met their needs. Specifically, they appreciated the deployability as during monsoon season they frequently need to move their shelter in order to avoid water accumulation. Although they do move their shelters, residents saw no need for the additional compaction, offered by the hinges. The roadside vendors thought the shelter was interesting but not well suited for their needs as they do not change locations and already have a compact setup. However, one of the vendors mentioned that some of the fruit vendors in Kullu do move between locations and thus the shelter may be useful in that scenario.

Discussion

The data revealed several considerations about the user set, the viability of an origami shelter for production, and the physical properties of an ideal structure. Overall, from the surveys, mathematical modelling of the shelter, and physical prototypes, it was clear that an origami shelter was best suited for stakeholders with a need for semi-permanent shelters. This user group included trekking companies, special event organizers, and temporary construction workers, among others. While the residents of the slums in Mandi are not ideally suited towards a semi-permanent, easily compactable shelter, with a few simple modifications, it would meet their needs and satisfy all of their needs. Traveling vendors and their families tend to rent apartments in each city, and required housing beyond the capacity of a shelter. Urban homeless users required a single personal structure that could be set up on the side of the road; although origami shelters are portable and can easily compact, on a small-scale they are heavier and less compact than tents and thus are not the best solution for this user group. From the interview with the trekking club advisor, it was clear that for an individual trekker, a tent was the best solution; however, he pointed out that many guide companies create semi-permanent base camps for their clients and this could be good market for origami shelters. Finally, although an origami shelter was best suited for semi-permanent use it can also have applications for users that need highly portable shelters.

In terms of the physical product, the initial full-scale prototype provided valuable feedback on manufacturing specifications and usage. While origami can produce simple and streamlined structures on a small-scale, the manufacturing limitations of full-scale structures reduce some of the benefits origami provides. For example, raw materials, including corriboard, come in specific sizes that are not large enough to create an entire structure from a single sheet; therefore joints are required which reduce the rigidity of the structure. Additionally, it is difficult to fold thicker materials such as corriboard, which makes it challenging to create accurate full-scale structures. To address some of these issues future versions should have accurate construction protocol, including jigs or fixtures for folding, less obtrusive attachments at the overlap joint, replace all seam joints with overlap joints, and any cutting or drilling should occur prior to folding. Additionally, the final prototype included hinges to aid in compaction but these proved to significantly degrade the rigidity of the structure and thus should be avoided in future versions.

The initial field-testing allowed the team to create a prioritized list of design changes for the final shelter by identifying the properties of an ideal shelter. Nearly all of the respondents indicated that the shelter was not compact enough and was difficult to transport, leading to several design changes in the final structure, which included folding the entire shelter into a single piece. Respondents also expressed displeasure with the initial floor setup of unattached tarp spread across the ground. To combat this, the team included a floor that firmly attached to the walls to provide full waterproofing. The temporary construction workers strongly desired a lock on the shelter and thus the final design has the ability to fully enclose and lock. The full list of design changes desired for the final shelter was as follows:

1. Better sealed and stronger joints
2. More compact when collapsed and easily transportable
3. Integrated floor
4. Full enclosure and lockable
5. Improved windows
6. Improved vertical height

The final design incorporated all of these features except for improved windows. Increased compaction was the only design change not to be received positively by either users or the designers. The final field-testing also revealed a list of new design changes for future versions:

1. Raised floor
2. Internal frame
3. Only use overlap joints and connect rigidly with metal strips or multiple bolts
4. Additional ventilation

These changes would reduce the shelters portability but greatly increase its rigidity and weather resistant and therefore make it more valuable for users with a need for semi-permanent shelters.

Project Outcomes

After 6 weeks of trial and feedback, the team completed a final full-scale origami shelter that met stakeholder design requirements and included a selection of 'smart' features. Additional deliverables included a manual documenting the assembly, compaction, and transport of the shelter as well as a list of features which can be added by stakeholders using built in mounts (see Appendix C, Supplemental Materials for this manual).

The base model origami shelter is about 6 feet tall, 5 feet wide, and 20 feet long, but is modular so both the length and width can easily be extended by adding more panels. It has the ability to fold down on both ends and lock to create a secure interior space. In addition to the water resistance, fire resistance, and rigidity provided by the material itself, the shelter comes with a standard selection of 'smart' features including: solar powered lighting and device charging, interior storage, ventilation, and a rainwater catchment system. Perhaps the single most important feature of this origami shelter is its extreme adaptability; only minor modifications to the base model are needed to customize the shelter for different users. For stakeholders such as the slum residents, who require a more permanent shelter, the width of the shelter can be extended by adding another panel, the hinge joints that aid in folding can be replaced by overlap joints to increase rigidity, extended vents can be incorporated, and detachable insulation can be added to the interior. For stakeholders such as trekking companies, special events organizers, and vendors, the shelter can be expanded or contracted by adding or removing panels and increased storage can be added. For stakeholders such as farmers, who may want to use the origami shelter as a greenhouse instead of as a shelter, the color of the corriboard can be changed to transparent or white to allow maximum light transmittance. Furthermore, increased storage solutions and overhead hooks to hang pipes from can be added, and the rain water catchment system can be routed back into the shelter to provide water for the interior plants. Changes in dimensions and switching hinge joints to overlap joints can be done based on the need of the stakeholder. While these are only a small selection of adjustments that can be made, they highlight the full extent of the range of adaptations can be made to the shelter to meet the specific needs of various stakeholders.

Although this version of the origami shelter is highly adaptable we recommend that future iterations of this project consider non-origami style shelters as well. Non-origami shelters can provide a lighter and more compact structure than origami structures that is more targeted for users requiring a small and highly portable shelter. These style of shelters may be well suited to the needs of both the urban homeless and local herders.

Additionally, while this version of the shelter is a versatile improvement over the previous version and other existing shelters it requires improvements to be marketable. These changes are addressed in in detail in the discussion but overall the team feels that the improvements to the rigidity are the most important as this shelter is designed for longer term use.

Conclusion

The final shelter was designed to be waterproof, fire resistant, lightweight, affordable, as well as include some 'smart' features such as solar power. The shelter produced met these requirements as confirmed by both laboratory and field-testing. The use of corriboard is an innovative feature that is not found in currently available origami shelters and provides the structure with the key benefits of being waterproof, fire resistant, and lightweight. For the area and volume achieved, this shelter is lighter than both the current shelters of temporary construction workers and the previous iteration of this project. Additionally, this shelter is modular and can be fully enclosed and locked which are features not found in many available shelters. The inclusion of 'smart' features such as solar power, water catchment, storage, and lighting make this shelter an improvement over available semi-permanent shelters in terms of extended use and quality of life. Overall, we have shown that origami can be used to create high-quality shelters for semi-permanent use and, while not ideal, it can additionally be used for small-sized temporary shelters or for permanent shelters.

The full report and supplemental materials for this project can be found at http://www.wpi.edu/E-project-db/E-project-search/search using keywords from the project title. Additional ISTPs can be found at http://www.iitmandi.ac.in/istp/projects.html.

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