McDonnell Academy
Global Energy and
Environment Partnership
(MAGEEP)

Reports of Funded Projects
2009 - 2010

Washington University in St. Louis
Preface

The McDonnell Academy Global Energy and Environmental Partnership (MAGEEP) was created after the First International Symposium on Energy and Environment held in May 2007 at Washington University in St. Louis. Today it is a network of 26 leading global Universities and Corporate Partners working collaboratively on global challenge issues related to energy and environment. Seed funding in the first round provided by Washington University in St. Louis led to the funding of 14 collaborative projects amongst the partner Universities. An educational project in aerosol science and engineering resulted in the creation of modules that are being used by several Universities worldwide.

A second round of seed funding was provided to support 11 projects. Reports of these projects are provided in this booklet. Projects ranged from those in Solar Energy, Bioenergy, Integrated Assessment, Energy and Environmental Issues in Rural Areas, Energy and Climate Analysis Frameworks, Policy Issues related to Renewable Energy, Water Quality, and Reducing Energy Demand in Commercial Buildings. Funds were also provided to students to have a Campus Clean Energy Competition. MAGEEP seed projects have spawned collaborative activity amongst the faculty and students from the various partner Universities. The Symposium on Global Energy Future is being held in St. Louis, October 1 to 5, 2010. Results of these collaborative projects will be discussed at this meeting. The Symposium will also provide for opportunities to initiate other fruitful collaborations. Our University campuses are living laboratories, and we also hope to exchange ideas for best practices in the areas of sustainable campuses. Areas where groups have come together include those for clean coal technology development; aerosol science and engineering; energy and environmental issues in development; bioenergy and solar energy utilization. A notable development is the networking of students from MAGEEP Universities – with more than 700 students now networked.

We thank the members of the Advisory Committee (http://mageep.wustl.edu/Board.aspx) of MAGEEP for helping promote collaborative research at the Partner Universities.

Pratim Biswas
Director, McDonnell Academy Global Energy and Environmental Partnership
http://mageep.wustl.edu

“Energy and environmental issues represent the greatest challenges of this century. This international conference has stimulated premier universities around the world to marshal their human and financial resources to meet these grand challenges. Many of the world's most talented students and academic leaders are poised to assure a brighter, sustainable future. We call on all segments of society to join us in this vital effort to secure this future.

International cooperation and collaboration will accelerate the progress in meeting the challenges associated with energy needs, assuring clean water and air, and addressing the global consequences from the accumulation of greenhouse gases. Research universities have the responsibility to prepare the next generation of leaders in the professions, in business, in government and in academia”.

Excerpts from Call to Action, Statement by Chancellor Mark Wrighton
Introduction

The McDonnell International Scholars Academy is a hub of international activities at Washington University and is central to our vision of a global university. A core mission of the Academy is to recruit future global leaders from our partner institutions and enable them to pursue graduate and professional degrees at our institution. These Scholars provide much of the “glue” between Washington University and the premier universities from around the world that make up the Academy network.

During the three first years of the Academy’s existence the number of partner universities has grown to 25, and more than 40 Scholars have come into its program. In addition to pursuing their doctoral or professional degree studies, these Scholars learn about American politics and culture, and they participate in leadership development programs such as trips to Washington, D.C. and New York to meet figures in government, business, and the professions.

A second mission of the Academy is to be an incubator of new ideas in research and education. Building on the research and teaching collaboration it has established with its partner institutions, the first topic taken up by the Academy has been energy and the environment. The 1st International Energy and Environment Symposium held in St. Louis in 2007 convened a group of researchers, students, corporate representatives, and civic leaders from around the world to address one of the most pressing issues facing the world today. The 2nd Symposium was held in December 2008 in Hong Kong. We are now meeting for the third time to discuss challenging issues related to global energy and the environment.

Launched as the McDonnell Academy Global Energy and Environment Partnership (MAGEEP), the initial effort awarded 14 research grants in 2007 for projects on a wide range of topics. The second funding resulted in 11 new projects, including one organized by doctoral students. This volume provides reports from these projects.

The McDonnell Academy and Washington University are committed to the idea that problems like providing society with clean safe energy and reducing environmental degradation are global in nature and require global solutions. Among other things, this suggests a new kind of worldwide partnership among research universities. The studies reported here represent the first product of our effort in this regard, and we take them to be a first step in an effort to address issues of energy and environment on a global scale.

James V. Wertsch
Director, McDonnell International Scholars Academy
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Oxidative Treatment of Industrial Wastewater: Development of Novel Catalysts and Technology Evaluation

P. A. Ramachandran (WUSTL), Professor
E-mail: rama@wustl.edu

D. P. Combset (WUSTL), Graduate Student
Email: dcombest@seas.wustl.edu

A. Garg (IIT, Mumbai), Professor
E-mail: a.garg@iitb.ac.in

B. Yadav (IIT, Mumbai), Graduate Student
E-mail: br_yadav@iitb.ac.in

1 Introduction and Background

Some chemical industries, such as pulp and paper mills or distillery units, are water intensive and use large quantities of fresh water in the process. As a result, enormous amounts of wastewater are produced that contain a number of organic and inorganic compounds depending upon the nature of input material. Many of these compounds are not amenable to biological treatment (i.e. lignin) but are highly toxic to the environment. Hence wastewater from such industries requires a primary oxidative degradation prior to biological treatment. With water becoming a scarce commodity, more so than even crude oil, the importance of this research need not be overstated. Development of efficient catalyst which operates at modest conditions is critical to the economics of this process. Furthermore, since the system involves a three phase catalytic reactor, the study of kinetics and transport effects is needed to guide the choice of the best reactor type and optimal design. The focus of this project is to address these issues and guide in the development of more advanced and cost effective technologies in this area.

Wet oxidation (WO) process is an attractive treatment method for wastewater having high chemical oxygen demand (COD) in comparison to biochemical oxygen demand (BOD$_5$) (BOD$_5$/ COD < 0.5). Some of the industries like pulp and paper mills may have extremely low BOD$_5$/COD ratio (~ 0.24) due to the presence of woody materials such as lignin and other cellulosic materials. Similarly, distillery wastewater and textile industries also contain chemical compounds originated from wood. Therefore, a pretreatment process is needed to make the wastewater suitable for subsequent biological treatment processes to reduce the COD to acceptable levels. WO process involves the liquid phase oxidation of oxidizable organic and inorganic matters at elevated temperature (up to 300 °C) and pressure conditions (up to 20 MPa). The source of oxygen may include molecular oxygen, air, H$_2$O$_2$, O$_3$ etc. and a suitable catalyst (preferably heterogeneous in nature) need to be present in the reactor. The organic compounds are converted into innocuous end products like H$_2$O, CO$_2$ etc. and no solid residue are formed after the reaction. However, it is evident from the literature that the destruction of recalcitrant compounds requires very high operating conditions that makes the implementation of the
process difficult in practice due to very high costs involved. The severity of oxidation reaction can be reduced by adding some suitable catalyst and auxiliary oxidant that could progress the reaction without affecting the final removal efficiencies. Hence the studies should be focused on the search of a suitable catalyst-oxidant combination and the optimization of the reaction conditions for efficient reduction in COD. In addition, other attributes (i.e. surface area, leaching properties and deactivation kinetics) of the catalyst must be investigated in order to assess its durability and cost-effectiveness.

2 Overall Research Objectives and Scope

The characteristics of high activity, cheap manufacturing costs, and long lifetime are highly desirable when designing a catalyst for industrial usage. For waste treatment processes, the reality is that the cost of treating the waste stream must be as low as possible since no revenue is made from processing a waste effluent. The research objectives and scope of the project includes:

1. Develop a catalyst that catalyzes the oxidation of ferulic acid (model lignin compound) in the presence of air at mild temperatures and pressures.
2. Develop a kinetic model that sufficiently details the behavior of the system.
3. Develop a reactor model to describe the behavior of the process on the industrial scale in order to estimate an overall mass balance, energy requirements, and the economics of the process.

3 Research Approach and Key Results

3.1 Catalyst Development and Experimental Work

To simulate the lignin containing effluent stream from a pulp and paper mill, ferulic acid (C_{10}H_{10}H_{4}) is chosen as a model compound and is show in figure 1. Both wet oxidation (WO) and catalytic wet oxidation (CWO) in the presence of air is performed on samples containing ferulic acid in water. The catalyst investigated for this research was chosen to be CuO/CeO$_2$, based on previous work by Dr. Garg and his graduate student B. Yadav [3].

![Ferulic Acid Molecular Structure](image)

Figure 1: Ferulic Acid Molecular Structure

The catalyst was prepared using co-precipitation, solgel (SG) and impregnation methods. The prepared catalyst was characterized by conducting X-ray diffraction (XRD), scanning electron microscopy - energy dispersive X-ray spectroscopy (SEM-EDX) and particle size analysis. The exact details are outlined in a thesis by B Yadav [3].

The reactions were carried out in a high pressure stainless steel batch reactor with an impeller and internal heating/cooling coils. The rate of mixing was controlled through manipulation of
the impeller rotation speed. Total organic carbon (TOC) was chosen as a measure of reaction progress for simplicity and was collected throughout the duration of each experiment. To ensure that the measured results did not exhibit mass transfer effects, a mixing study was performed. Specifically the impeller speed (rotations per minute (RPM)) of the reaction mixture was increased until no noticeable change in TOC was seen between the rates of agitation at the same time t. This is seen in Figure 2 as the rate of mixing was increased from 250 RPM to 1200 RPM. It can be safely concluded that at 1000 RPM, gas-liquid mass transfer effects have been minimized.

![Figure 2: Agitation study comparing TOC reduction over various RPM levels](image)

The catalyst was shown to be active in the catalytic wet oxidation process, reducing the total organic carbon (TOC) in the system a significant amount (50-75 percent of original TOC) at moderate temperatures and pressures (T = 90-150 C and P = 1 MPa). The increased reduction of TOC in the reaction mixture for increasing temperature is seen in Figure 3. The TOC versus time data was collected at various process temperatures, with or without the developed catalyst, and provided to Dr. Ramachandran and D. Combest at WUSTL to perform kinetic model derivation for further process modeling. The kinetic modeling work is outlined and discussed in the next section.

3.2 Kinetic Modeling

3.2.1 The Simple TOC Based Model

During the catalyst development and experimental portion of the project, total organic carbon (TOC) versus time data was collected at various process temperatures, with or without the developed catalyst. Given the nature of the data collected, the most natural method to describe the chemical kinetics during the oxidation process utilizes the measure of TOC as a primary variable. Specifically, all organic species are lumped into a single component (A) that undergoes a complete oxidation with O\textsubscript{2} to form the product CO\textsubscript{2} and H\textsubscript{2}O. This overall reaction lumps all of the elementary chemical reactions steps taking place throughout the process together into an overall reaction shown as:
Figure 3: Simultaneous catalytic/non-catalytic TOC reduction for various reaction temperatures.

\[
A + O_2 \xrightarrow{k_{1, \text{non-catalytic}}} CO_2 + H_2O \quad (1)
\]

\[
A + O_2 \xrightarrow{k_{2, \text{catalytic}}} CO_2 + H_2O \quad (2)
\]

Reaction 2 represents the overall catalytic reaction between the species and heterogeneous catalyst, while reaction 1 represents the overall non-catalytic reaction of the organic species and O\textsubscript{2} in the bulk liquid. For a simple TOC based reaction rate model the rate of disappearance of the organic species in solution is expressed as:

\[
-r_A = k_1[TOC][O_2] \quad (3)
\]

\[
-r_A = k_1[TOC][O_2] + k_2[\text{cat}][TOC][O_2] \quad (4)
\]

\[
k_n = k_{n,o} \exp\left\{ \frac{-E_{a,n}}{RT} \right\} \quad (5)
\]

\[
n = 1 \quad \text{and} \quad 2 \quad (6)
\]

with equation 3 describing the non-catalytic reaction (single parameter TOC model) and equation 4 describing the simultaneous catalytic/non-catalytic reactions (2 parameter TOC model). This kinetic expression is fitted to TOC/TOC\textsubscript{o} vs. time curves at multiple temperatures for catalytic and non-catalytic results to obtain activation energies (\(E_{a,n}\)) and pre-exponentials (\(k_{n,o}\)) in equation 5 with temperature \(T\) and universal gas constant \(R\).

Equations 4 and 3 describe reactions 1 and 2 rather poorly (Figure 4 and 5) compared to a more advanced model described in later sections. Though the simple TOC based models are easy to implement, there are minor problems with this approach when modeling the overall mass transfer with chemical reaction that will be more evident in a later section. In general, the use of TOC allows the chemist and engineer to group the vastly complex reactions seen the oxidation of organic compounds into one term. The value of TOC is readily calculated with
TOC analyzers, yet the numerous intermediates are often ignored and the overall reaction is used to judge the effectiveness of a catalyst alone. In this study we are judging the efficacy and feasibility of a catalyst through both kinetic modeling and process modeling. Because the TOC values collect the values of the intermediates, it also masks the physical attributes of the reaction mixture. In short there is no way to lump the viscosity, diffusivity, mass transfer coefficients, etc. together in a similar manner to TOC measure. Furthermore, modeling the process energetics using the activation energies from reaction rate equations 4 and 3 is impossible since one can not determine how many moles of a specific molecule are present based on the TOC. This makes process modeling entirely empirical with the current kinetic model stated in equation 4 based on reactions 1 and 2. To overcome the limitations of the use of TOC as the primary variable in the proposed kinetic model, a simplified lumped kinetic model similarly outlined by Zhang and Chuang may be used [4].

3.2.2 The Lumped Kinetic Model

A simplified lumped kinetic model similarly outlined by Zhang and Chuang may be used [4] to describe the non-catalytic homogeneous reactions. The model supposes that the reaction takes place in multiple steps, where only the intermediates are lumped together. Given the following partial oxidation (reaction 8) and deep oxidation (reaction 7) reactions:

\[ A + 10.5O_2 \xrightarrow{k_1} 10CO_2 + 5H_2O \]  
\[ A + \nu_{(2,2)}O_2 \xrightarrow{k_2} \nu_{(2,3)}B + \nu_{(2,4)}H_2O \]

with the starting single component substrate represented as A and organic intermediate compounds lumped into B so that:

\[ TOC = [A] + [B] \]  
\[ [CO_2] = [A]_0 - TOC \]

The terms \([A]\) and \([B]\) must then represent the total concentration of carbon within substrate and the lumped intermediates respectively. To determine the molar concentration of A, \([A]\) must be divided by the number of carbons in the substrate molecule. In this case, ferulic acid contains 10 carbon atoms. This is an important note to remember when determining the actual concentration of ferulic acid.

Using reactions 7 and 8, the rate of disappearance of A and appearance B in the bulk liquid is expressed as:

\[ -r_A = \frac{d[A]}{dt} = k_1[A][O_2]^{n_1} + k_2[A][O_2]^{n_2} \]  
\[ r_B = \frac{d[B]}{dt} = k_2[A][O_2]^{n_2} \]

If there are no mass transfer limitations, \(O_2\) concentration is equal to the solubility and is maintained at a constant value. This allows for further simplification so that:

\[ k'_1 = k_1[O_2]^{n_1} \]  
\[ k_2 = k_2[O_2]^{n_2} \]
Where the oxygen term in equations 13 and 14 are be found using Henry’s law \([O_2] = (\text{Henry’s law constant})(\text{Partial pressure of O}_2 \text{ in the reactor vessel})\). Also, for simplicity, \(n_1\) and \(n_2\) may be assumed to be 1. This assumption has been shown to allow a good model fit to experimental data by previous work by Guo [1].

The initial conditions for the system are assumed to be \(t=0, [A]=[A]_0=\text{TOC}_0, \text{ and } [B]=0\). At time \(t\), \([A]=[A], [B]=[B], \text{ and } [A]+[B]=\text{TOC}\). Integrating equations 11 and 12 from 0 to \(t\), the resulting equations are:

\[
\ln \left( \frac{[A]_0}{[A]} \right) = (k'_1 + k'_2)t
\]

\[
[B] = \frac{[A]_0k'_2}{k'_1 + k'_2}(1 - \exp(-(k'_1 + k'_2)t))
\]

Using initial condition and equations 11-16, we may obtain:

\[
\frac{\text{TOC}}{\text{TOC}_0} = \frac{k'_2}{k'_1 + k'_2} + \frac{k'_1}{k'_1 + k'_2}\exp \left( - \left( k'_1 + k'_2 \right) t \right)
\]

Using \(\text{TOC}/\text{TOC}_0 \) versus time data at multiple temperatures, a nonlinear fit of equation 17 may be performed on the data to obtain values for \(k'_n\) values. The fitted equation 17 is shown to be in better agreement than the original single parameter TOC based rate equation (equation 3) in Figure 4. From these \(k'_n\) values, the activation energies in the \(k_1\) and \(k_2\) terms in equations 13 and 14 can be found. These may then be used in process modeling.

![Figure 4: Comparison of non-catalytic model fitting of simple TOC based rate equation (equation 3) to a 2 parameter lumped kinetic model (equation 11)](image)

To include the catalytic processes, additional chemical equations must be included. Again the same approach by Zhang and Chuang is used [4], only applied to the heterogeneous catalytic processes. The chemical reactions for the simultaneous catalytic and non-catalytic reaction system are assumed to be:
Non-Catalytic Reactions

\[ A + 10.5O_2 \xrightarrow{k_1} 10CO_2 + 5H_2O \]  \hspace{1cm} (18)

\[ A + \nu(2,2)O_2 \xrightarrow{k_2} \nu(2,3)B + \nu(2,4)H_2O \]  \hspace{1cm} (19)

Catalytic Reactions

\[ A + 10.5O_2 \xrightarrow{k_{3,\text{catalyst}}} 10CO_2 + 5H_2O \]  \hspace{1cm} (20)

\[ A + \nu(4,2)O_2 \xrightarrow{k_{4,\text{catalyst}}} \nu(4,3)B + \nu(4,4)H_2O \]  \hspace{1cm} (21)

The rate of disappearance of species A and appearance of B in the reaction mixture is defined as:

\[-r_A = \frac{d[A]}{dt} = k_1[A][O_2]^{n_1} + k_2[A][O_2]^{n_2} + k_3[A][\text{cat}][O_2]^{n_3} + k_4[\text{cat}][A][O_2]^{n_4} \]  \hspace{1cm} (22)

\[ r_B = \frac{d[B]}{dt} = k_2[A][O_2]^{n_2} + k_4[\text{cat}][A][O_2]^{n_4} \]  \hspace{1cm} (23)

If there are no mass transfer limitations, \(O_2\) concentration is equal to the solubility and is maintained at a constant value. This allows for further simplification so that:

\[ k'_1 = k_1[O_2]^{n_1} \]  \hspace{1cm} (24)

\[ k'_2 = k_2[O_2]^{n_2} \]  \hspace{1cm} (25)

\[ k'_3 = k_3[\text{cat}][O_2]^{n_3} \]  \hspace{1cm} (26)

\[ k'_4 = k_4[\text{cat}][O_2]^{n_4} \]  \hspace{1cm} (27)

Where the oxygen term in equations 24 - 27 is found using Henry’s law \(([O_2] = \text{(Henry’s law constant)} \times \text{(Partial pressure of O}_2\text{ in the reactor vessel)})\). Also, for simplicity, \(n_1\) and \(n_2\) may be assumed to be 1. This assumption has been shown to allow a good model fit to experimental data by previous work by Guo [1]. It is also assumed that the catalyst concentration is homogeneous throughout the reactor vessel, making the \([\text{cat}]\) term constant for our analysis. Additionally, we are assuming that there are no mass transfer limitations of the species to the solid catalyst due to the high rate of mixing in the system. Also, the effect of intraparticle diffusion is assumed to be negligible due to the small size of the catalyst particles. Integrating equations 22 and 23 from 0 to \(t\) gives the relations:

\[ \ln \left( \frac{[A]_0}{[A]} \right) = (k'_1 + k'_2 + k'_3 + k'_4)t \]  \hspace{1cm} (28)

\[ [B] = \frac{(k'_2 + k'_4)[A]_0}{k'_1 + k'_2 + k'_3 + k'_4} \left( 1 - \exp\left(-\left(k'_1 + k'_2 + k'_3 + k'_4\right)t\right) \right) \]  \hspace{1cm} (29)

Using an initial condition similar to the non-catalytic derivation (earlier in this section), the conditions at \(t=0\) are \([A]=[A]_0=\text{TOC}_0\) and \([B]=0\). At time \(t\), \([A]=[A],\ [B]=[B],\ \text{and}\ [A]+[B]=\text{TOC}\). With the initial condition and equations 22-29, a relation between the ratio of \(\text{TOC}\) to \(\text{TOC}_0\) versus time is derived as:
\[
\frac{TOC}{TOC_0} = \frac{k'_2 + k'_4}{k'_1 + k'_2 + k'_3 + k'_4} \left( 1 - \exp \left( - \left( k'_1 + k'_2 + k'_3 + k'_4 \right) t \right) \right) + \exp \left( - \left( k'_1 + k'_2 + k'_3 + k'_4 \right) t \right)
\] (30)

Nonlinear curve fitting of TOC/TOC\(_0\) versus time data at multiple temperatures can be used to solve equation 30 for all unknown \(k'_n\) values. The fitted equation 30 is shown to be in better agreement than the original 2 parameter TOC based rate equation (equation 4) in Figure 5. Activation energies and preexponentials in the \(k_3\) and \(k_4\) terms can subsequently be solved. For this step, it is necessary to know the amount of catalyst ([cat]) present in the reaction mixture and assume values for \(n_3\) and \(n_4\) are equal to 1. With all unknowns, the rate equation (equation 22) for ferulic acid (species A) may be fully expressed.

Figure 5: Comparison of simultaneous catalytic/non-catalytic model fitting of simple 2 parameter TOC based rate equation (equation 4) to a 4 parameter lumped kinetic model (equation 22)

### 3.2.3 A Kinetic Model with Mass Transfer Effects

For further reactor and process modeling, one would need to include mass transfer effects of \(O_2\) through the gas-liquid and liquid-solid phases in the rate expression. A procedure for including mass transfer effects in a reaction rate is outlined by P. A. Ramachandran and R. V. Chaudhari [2]. If the only the heterogeneous portion of the rate equation =22 for species A is used, then the resulting quadratic equation representing catalytic reaction rate including mass transfer of \(O_2\) from the gas phase to the solid surface of the catalyst is:
\[-R_{A,\text{cat}} = \left( [O_2]^* - \frac{10.5 + \nu(4,2)}{2M_{O_2}} (-R_{A,\text{cat}}) \right) \left( [A]_L - \frac{(-R_{A,\text{cat}})}{k_3a_p} \right) \left( k_3'' + k_4'' \right) \quad (31) \]

\[ k_3'' = k_3[\text{cat}] \quad (32) \]
\[ k_4'' = k_4[\text{cat}] \quad (33) \]
\[ M_{O_2} = \left( \frac{1}{K_La_b} + \frac{1}{k_s a_p} \right)^{-1} \quad (34) \]

With $[O_2]^*$ equal to the liquid concentration of oxygen given by Henry’s law; $[A]_L$ represents the liquid phase concentration of ferulic acid; $M_{O_2}$ represents the overall mass transfer of oxygen from the gas phase to the solid surface; with $K_La_b$ and $k_s a_p$ defined as interphase mass transfer coefficients discussed in [2].

Solving the rate equation 31 for $-R_{A,\text{cat}}$ gives the rate of catalytic reaction in the system including mass transfer. This rate equation, along with equation 11, may be used with a standard process modeling approach such as the Axial Dispersion Model (ADM). From an ADM approach, process energetics and preliminary economics can be investigated.

3.3 Process Modeling

3.3.1 Reactor Models

Currently we have implemented an axial dispersion model as a solver in OpenFOAM, a computational fluid dynamics modeling software. OpenFOAM is a C++ library capable of solving highly coupled systems of partial differential equations (PDE). For the ADM solver, a 1-dimensional PDE is solved for ferulic acid and oxygen through a trickle bed reactor.

3.3.2 Process Modeling

The process modeling aspect of the project uses SuperPro Designer with input from the reactor modeling portion. The reactor models will provide overall conversion and mass balance information for SuperPro Designer. With this input, process economics can be determined to help evaluate the catalyst.

4 Resulting Presentations, Publications, and Proposals

Presentation

This work will be presented at the Annual AIChE meeting in Salt Lake City, NV in November of 2010. The talk will highlight the collaboration between IIT-Bombay and WUSTL, discussing the experimental and modeling aspects of the project.

Publications

With additional experimental work and modeling effort, multiple publications could result from this project. The publications will discuss the novel kinetic models developed to describe both the catalytic and non-catalytic wet oxidation process, as well as the axial dispersion model used in the process modeling portion of the work.
Proposals

A proposal for additional funding will be submitted to continue the experimental and modeling work. Funding will be sought from NSF/DST as well as directly from the pulp and paper mill industry in the US and India including International Paper (NYSE:IP), Clearwater Paper Corp. (NYSE:CLW), Kapstone Paper and Packaging Corp (NYSE:KS), or The Procter & Gamble Company (NYSE:PG). Additionally, the formation of a clean water consortium through MAGEEP would be beneficial in further funding of this project and gain the direct support and collaboration of industrial partners.

5 Conclusions and Recommendations for Future Work

The experimental work by B. Yadav and Dr. Garg at IIT Bombay provided enough data to model the reaction kinetics as a simple 2 and 4 parameter lumped model, similar to an approach outlined by Zhang and Chuang [4]. It was found that the proposed kinetic model showed an agreeable fit with the experimental data provided, but further work is necessary to conclude that the lumped kinetic models accurately describe the consumption of ferulic acid. This would be achieved by additional experimental studies providing ferulic acid concentration versus time data in conjunction with TOC/TOC$_0$ versus time data for both catalytic and non-catalytic reactions. Additionally, more studies investigating catalyst loading would enable a better fit of the 4 parameter lumped model. With further improvements to the lumped kinetic models, the reactor models would be more realistic, capturing more reliable behavior that could be used as input into a process model. As an additional area of investigation, catalyst development work would benefit from molecular scale modeling to determine intermediates and possible products of the catalytic oxidation, enabling more detailed kinetic and resulting reactor and process models. Lastly, the entire process of judging the efficacy of a catalyst depends not only on the performance in the laboratory but through a quantitative measure of performance on the reactor and process scale through reactor and process modeling.

References


INTRODUCTION

Using Computational Fluid Dynamics (CFD) software, four different cooling systems used in contemporary office environments are modeled to compare energy consumption and thermal comfort levels. Incorporating convection and radiation technologies, full-scale models of an office room compare arrangements for (a) an all-air overhead system (mixing ventilation), (b) a combined air and hydronic radiant system (overhead system with a chilled ceiling), (c) an all-air raised floor system (displacement ventilation), and (d) a combined air and hydronic radiant system (displacement ventilation with a chilled ceiling). The computational domain for each model consists of one isothermal wall (simulating the exterior of the building) and adiabatic conditions for the remaining walls, floor, and ceiling (simulating interior walls of the room). The computations are performed for an isothermal exterior wall that changes temperature as a function of time simulating the temperature changes on the exterior wall of the building throughout a 24 hour period. Results show superior thermal comfort levels as well as substantial energy savings can be accrued using the displacement ventilation, especially the displacement ventilation with a chilled ceiling over the conventional mixing ventilation system.

TYPES OF COOLING/VENTILATION SYSTEMS

Conventional Variable-Air-Volume (VAV) Ventilation

In general, buildings, especially modern designs, are tightly constructed with low leakage rates from materials that provide high thermal insulation. In the simplest HVAC systems, where all-air overhead ventilation relies on turbulent mixing of room air with ventilated air, the mechanical air-conditioning must overcome the internal heat loads in a very direct way. The
internal heat loads typically consist of heat plumes created from occupants, lights, and office equipment (including electronic devices on standby). The conventional office and industrial building design criteria for ventilation are based on the need to remove this excess heat (and pollutants) rather than to provide adequate air for respiration. A person requires about 7.5 liter/min for respiration [1].

In addition, for the typical mixing system, initial construction costs are low and it requires little maintenance; however, because of the large volume of air needed for heat exchange, this results in an increase in space allocation in comparison to the alternative systems. This increased space requirement typically results in greater building envelope surface area, and an associated increase in envelope heating and cooling loads. Given these factors, it is reasonable to assume that considerable inroads towards energy efficiency can be made by modifying these traditional HVAC systems.

**Displacement Ventilation**

A superior system is the displacement ventilation (DV) system in which ventilated air is dispersed at low speeds along the floor (or near the floor along the walls) and is warmed by internal heat sources (occupants, lights, plug-in equipment) as it rises to the top, displacing the air already present. DV is more effective at removing contaminants than conventional turbulent mixing ventilation, while permitting a smaller airflow rate by a factor of two [2]. In addition, the supply air temperature for DV is significantly higher for the same comfort conditions (about 18°C versus about 13°C in a conventional mixing ventilation system), reducing the chilling load significantly. Depending on the regional climate, DV can reduce energy use for cooling and ventilation by 30-60% [3, 4].

**Displacement Ventilation with Radiant Cooling**

The radiant (hydronic) heating/cooling system provides even greater potential for energy efficiency. Water is 25-100 times more effective than air at transferring heat energy. Thus, tremendous efficiency gains can be made by decoupling the ventilation from the heating/cooling load. In general, this decoupled system circulates chilled or hot water through the ceilings and walls of office buildings and the floors of residential units for temperature control, while only distributing the volume of air required for ventilation. This decoupled system allows for 100% of the ventilated air to be from the outside rather than re-circulating a portion of the indoor air, thereby providing health benefits. For example, it is not uncommon for conventional HVAC systems to re-circulate up to 80% of the internal air on each circuit and replace the remaining 20% with fresh air [5]. Also, further energy gains are achieved because the internal heat plumes generated by occupants, lighting, and plug-in equipment (constituting up to 30% of total cooling requirement [5]) are vented directly outside rather than partly re-circulated, as in a conventional system. Using a decoupled system with constant ventilation can produce savings of 20-30%. It should be noted that the required airflow – now decoupled from heating/cooling functions – can be made to vary with changing building occupancy. A demand controlled ventilation (DCV) system uses CO2 and/or other sensors to adjust the ventilation rate; this can reduce total HVAC energy by an additional 20-30% compared to fixed rate ventilation based on maximum occupancy [6].

In a chilled ceiling system, a large fraction of the ceiling is chilled by circulating cold water through pipes or lightweight panels. In addition to the aforementioned increased effectiveness of water over air in transporting heat, there is a reduced cooling load, since typically water is supplied at 16-20°C rather than 5-7°C, as in conventional hydronic cooling systems. Not only does this reduction in cooling load allows a higher chiller coefficient of performance (COP, or cooling power divided by fan power - a direct measure of efficiency), but it also allows more frequent use of ‘water-side free cooling’, where the mechanical chilling is bypassed altogether and supplied water for space cooling comes directly from a cooling tower.

In the case of conventional dehumidification systems with air-conditioning, dehumidification is accomplished by overcooling the air so that sufficient water vapor is condensed, and then the air is reheated to be supplied at a comfortable temperature. Dehumidification can be decoupled
from cooling through a variety of desiccant-based techniques, with energy use savings of 25-
30%, or by up to 50% if solar heat is used to regenerate the desiccant [7]. Lastly, perceived temperature depends on more than just air temperature and its velocity. Infrared radiation from surrounding surfaces also plays a role, especially if there is significant radiant asymmetry. Infrared radiation depends on the temperature and emissivities of the surfaces enclosing the occupied space. As a result, radiant asymmetry happens when there is one surface, such as a window or exterior wall that is much hotter than other surfaces such as the interior walls. Likewise, humans emit infrared radiation and if the emission of the surrounding surfaces and its subsequent absorption is greater than that of the human, then the person will feel warm even if the air is cool. Therefore, in the case of radiant cooling, the set points for temperature and humidity can be adjusted higher due to the perceived temperature difference from traditional ventilation systems.

RESEARCH APPROACH

CFD Flow Solver
FLUENT is a general-purpose CFD code, which solves the Unsteady Reynolds-averaged Navier-Stokes (URANS) equations using the finite-volume method on a collocated grid. It can model fluid flow and heat transfer in complex geometries using an interactive, menu-driven interface. It can solve 2- and 3-D problems in steady and unsteady simulations. FLUENT has the capability to solve incompressible and compressible flows using inviscid, laminar, and turbulent viscosity models. There is a wide array of turbulence models available, including Spalart-Allmaras (S-A), k-ω, and k-ε (Standard, RNG, Realizable) models.

Setup for Flow Field Computations
The initial starting values of temperature, $T_0 = 288.16$ K, and density $\rho_0 = 1.225$ kg/m³, are employed. Discrete-ordinate method for the radiation calculation is employed. The governing equations are solved using the first-order-upwind scheme and the pressure is calculated using the PRESTO! scheme. The SIMPLE algorithm is employed for the coupling of the velocity and pressure. The Spalart Allmaras (S-A) turbulence model is employed. The S-A is a simpler turbulence model, which only uses one equation to describe the turbulent eddy viscosity, compared to the k-ε (RNG) model, which employs two equations to calculate the eddy viscosity.

Temperature Controller
The temperature controller was designed and coded into the Fluent by a user defined function (UDF) so that it maintained a band of temperatures deemed comfortable, 72.4F to 76.0F (295.6K to 297.6K). The controller was setup such that if the temperature reached the upper set point in the controller, the mass flow inlets would turn on and drive the temperature down to the lower set point, at which the jets would turn off. Fig. 1 shows the behavior of the temperature controller as it cycles the mass flow inlets.
Constant mass flux was specified across the mass flow inlets. The controller read the temperature 3" off of the rear wall and halfway between the floor and the ceiling, and the two side walls. This was done to simulate realistic placement of the thermostat inside of the room. The temperature controller is cycled at 3 minute intervals.

**Exterior Wall Temperature Wave Form**

A Fluent user defined function (UDF) was created to simulate the temperature of the exterior wall of the room. This temperature curve simulated the exterior surface and was based on an ASHRAE TETD curve.
Exterior Wall Modeling

The exterior wall was modeled after traditional glazed window construction with a window shade. The materials, layer thicknesses and properties are given in Table 1.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>ρ [kg/m³]</th>
<th>C_p [J/kg-K]</th>
<th>k [W/m-K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulated Glass Unit (IGU)</td>
<td>1”</td>
<td>2500</td>
<td>840</td>
<td>0.0405</td>
</tr>
<tr>
<td>Air</td>
<td>1”</td>
<td>1.225</td>
<td>1006.43</td>
<td>0.0242</td>
</tr>
<tr>
<td>Plastic Shade</td>
<td>1/32”</td>
<td>905</td>
<td>1670</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Pre-Processing: Mesh Generation

Case 1

Case 1 was created to simulate the conventional variable-air-volume (VAV) ventilation system. A 3-D Cartesian mesh inside Case 1 was generated by GAMBIT, with a uniform grid of spacing of 3” [Figs. 3-5]. The exterior wall layers were meshed with each layer having 3 nodes across their thickness.

Despite the steep gradients near the walls, this spacing is sufficient to capture the flow field with reasonable accuracy. This mesh has a cell count of 87,552 and a node count of 110,322.

Case 1’s vent was sized based on HVAC requirements. The inlet and outlet dimensions of the vents are 9” x 36” (0.2286m x 0.9144m) spaced 12” (0.3048m) off of the rear wall shown in Fig. 6, which gives an area of 2.25 ft² (0.2090 m²) for each vent.
Case 1 has a volume of 1,368 ft³ (38.74 m³). By meeting the guidelines of four air changes per hour [8], this vent size gives a flow velocity of 40.54 ft/min (0.206 m/sec).

**Case 2**

Case 2 was created to simulate the conventional variable-air-volume (VAV) ventilation system with radiant cooling. Case 2’s vents were of the same size and position as of Case 1. Case 2 has the addition of the radiation slab, 72” x 72” x 6”, which provides the chilled ceiling effect [Fig. 7]. The radiation slab is placed 6” below the ceiling in the center of the room.

The Case 2 mesh varies slightly from the Case 1 mesh, since the radiation slab is included in Case 2. Consequently the volume for Case 2 is also slightly smaller than Case 1 (Case 2 Volume = 1,350 ft³ (38.228 m³)). A 3-D Cartesian mesh inside Case 2 was generated by GAMBIT, with a uniform grid spacing of 3” [Figs. 8-10]. The exterior wall layers were meshed with each layer having 3 nodes across their thickness.
Despite the steep gradients near the walls, this spacing is sufficient to capture the flow field with reasonable accuracy. This mesh has a cell count of 97,344 and a node count of 109,793.

The discrete-ordinate radiation model was employed for heat transfer calculations due to radiation. This adds another term $q_{\text{radiation}}$ to the total surface heat flux from a given surface. Fluent calculates the values for $q_{\text{radiation}}$ and $q_{\text{convection}}$ for the chilled ceiling. The radiation block is made of weathered stainless steel with external emissivity of 0.85. The walls (hot wall and adiabatic walls) are gray and diffuse and have an absorption coefficient of 0.85. The air has an absorption coefficient of 0.17 to account for the water vapor [9]. Thus, radiation is transferred from the slab to the air and walls. Note that after the radiation transfers heat to the walls, the portion of heat that is not absorbed is diffusely reflected onto the air and to the other walls.

**Case 3**

Case 3 was created to simulate a distributed ventilation (DV) system. Fig. 11 shows the schematic of Case 3 with the two outlet vents in the ceiling and six inlet vents on the floor.

Case 3’s inlet vents are designed to have the same total inlet vent area as Case 1 and 2. There are six inlet vents on the floor. Hence, the Case 3 inlet vents are 6" x 9", which gives an area of 2.25 ft$^2$ (0.209 m$^2$) for six vents (Fig. 7). Since there is no change in the total inlet vent area compared to Case 1, Case 3 meets the ASHRAE guidelines of air movement in the room. The six inlet vents are placed on the floor near the adiabatic walls. The outlet vent area of Case 3 is double the size of the outlet vent area of Case 1. Each outlet vent is of the size, 9" x 36" (0.2286m
x 0.9144m) spaced 12”, giving an area of 4.5 ft² (0.418 m²)) for the 2 outlet vents in Case 3. Case 3 has a volume of 1,368 ft³ (38.74 m³).

A 3-D Cartesian mesh inside Case 3 was generated by GAMBIT, with a uniform grid spacing of 3” [Figs. 12-14]. The exterior wall layers were meshed with each layer having 3 nodes across their thickness.

This mesh has a cell count of 100,320 and a node count of 112,233.

**Case 4**

Case 4 was created to simulate a distributed ventilation system with radiant cooling. There are no changes in the sizes or placement of the inlet or outlet vents from Case 3, so Case 4 meets the ASHRAE guidelines of air movement in the room. Case 4 has the addition of a 72” x 72” x 6” radiation slab that provides the chilled ceiling effect [Fig. 15]. The radiation slab is placed 6” below the ceiling in the center of the room.

Similar to Cases 1, 2 and 3, a 3-D Cartesian mesh inside Case 4 was generated by GAMBIT, with a uniform grid spacing of 3” [Figs. 16-18]. The exterior wall layers were meshed with each layer having 3 nodes across their thickness.
The Case 4 mesh varies slightly from Case 3, since the radiation slab is included in Case 4. Consequently the volume for Case 4 is also slightly smaller than the other two cases (Case 4 Volume = 38.228 m³). This mesh has a cell count of 99,120 and a node count of 111,681. The same radiation model as in Case 2 is utilized in Case 4.

**KEY RESULTS**

These simulations utilize a mass flux of 0.252435 kg/s-m² and an inlet temperature of 60°F (15.6 °C). The time steps are 180 seconds (3 minutes). The data was taken on the second cycle so that there would not be a transient effect from the initialization of the flow field.
The cases without the radiation slabs (Cases 1 and 3) have their jets on for longer periods of time and more frequently than the cases including the radiation slabs (Cases 2 and 4). The cases with the distributed ventilation systems (Cases 3 and 4) have their jets on for less time and less frequently than their counterparts with the overhead system (Case 1 and 2).

Fig. 20: Average volume temperature and control point temperature for Cases 1, 2, 3 and 4

Fig. 20 shows the control point temperature following the average volume temperature closely in the two cases with the VAV system (Cases 1 and 2), while the cases with the distributed ventilation (Cases 3 and 4) vary several degrees from the control point. This is most likely caused by the position of the inlet and outlets in those cases.
The distributed ventilation system with the radiation slab (Case 4) requires the least amount of chilled air to maintain thermal comfort [Fig. 21]. Case 2 requires the next smallest amount of chilled air followed by Case 3 and Case 1. Cases 2, 3 and 4 require 30.99%, 15.79% and 50.29% less chilled air than Case 1 to maintain thermal comfort. This result is not surprising because Case 4 (distributed ventilation with a radiation slab) was thought to be the most efficient.

In order to calculate the energy being removed from the Cases by the jet, we must numerically integrate:

\[
\int m \cdot C_p \cdot \left( T_{jet} - T_{Room\text{--average}} \right) dt
\]

The radiation slab’s energy was calculated by numerically integrating:

\[
\int \text{flux} \cdot \text{area} \cdot dt
\]

where \( \text{flux} \) refers to the total surface heat flux measured on the radiation slab’s surfaces and \( \text{area} \) is the total surface area of the radiation slab.

The total energy removed from Cases 2 and 4 is the sum of the flow energy and radiation slab energy.
Fig. 22 shows that the total amount of heat being removed from Cases 1 and 2 and Cases 3 and 4 are similar. The small deviations are caused by the design of the cases and how the radiation slab affects the flow field. Since a chiller tower is cheaper to operate than an air conditioning unit, the cases with the radiation slabs will be cheaper to operate than the cases without the radiation slab.

CONCLUSIONS
1. The air conditioning energy needs can be reduced through the use of distributed ventilation and chilled ceilings. Assuming the energy requirements for a cooling tower are small in comparison to that for an air conditioning unit with similar capacity, the energy savings should be roughly proportional to the reduction in chilled air being supplied to each room. For the cases analyzed in this paper, there could be a 30.99% reduction in energy if there was a radiant cooler added to the traditional VAV system, a 15.79% reduction if a distributed ventilation system was used over the traditional VAV system and a 50.29% reduction in energy if a distributed ventilation system with a chilled ceiling was used over the traditional VAV system.
2. Full CFD analysis of each room is required because the manner in which the air enters and exits each room creates distinct flow fields whose behavior determines the efficiency of each ventilation system. For example, the DV system introduces cold air on the floor of the cases at low velocities. Temperature stratification is allowed to develop so that the hot air exits the room through the air outlets. The VAV system does not allow the stratification to take place due to the duct placement and higher air velocity; thus, the outlet air temperature is lower.

FUTURE WORK
1. It was found that the average volume temperatures of the cases differed from the temperatures being read by the temperature controller (most notably during the middle of the day when the vents in Case 1 were on continuously and Case 3’s vents were cycling). Simulations should be conducted with the temperature controller reading the average volume temperature as opposed to a single point temperature inside the room to determine if the same efficiency gains can be obtained with the DV system compared to the VAV system. For this purpose, adding additional control points inside the room should bring the energy efficiency analysis closer to that based on average volume temperatures. This is needed only during the hotter parts of the day.
2. Additional simulations should also be conducted to determine the changes in the energy requirements for cooling in different climate conditions in different parts of the U.S and the world. The influence of temperature controller setting on energy requirements should also be estimated since it is likely to be nonlinear.
3. Additional simulations should be conducted with a heated floor and a temperature boundary condition that simulated winter conditions to see the effects of different ventilation and heating systems.

**PLANS FOR FUTURE COLLABORATION**
The PI and Co-PI will continue their collaboration to further the research in this area. It is possible that the ICARES Professor Christof Jantzen may also join the team. The collaboration will continue with Professor Ismail Tuncer of the Middle East Technical University in Turkey. The possibility of collaboration with other international partners in MAGEEP will also be explored.

**PUBLICATIONS AND PROPOSALS**
Professors Donnelly and Agarwal had submitted a proposal to DOE which was not successful. They again plan to submit a revised proposal to DOE this year. The results reported in this paper are being prepared in a manuscript that will be submitted for publication in the ASHRAE Transactions.

**REFERENCES**
Electrospray Fabrication of Porous TiO$_2$ Films For Dye/Polymer-sensitized Solar Cells

Investigator: Da-Ren Chen$^1$
Co-Investigators: Chih-Chieh Chen$^2$ and Ruth Chen$^1$

$^1$Department of Energy, Environmental and Chemical Engineering, Washington University in St. Louis, St. Louis, MO 63130

$^2$Institute of Occupational Medicine and Industrial Hygiene College of Public Health, National Taiwan University

Submitted to Prof. Pratim Biswas (jwertsch@wustl.edu)
With copy to Kim Colemen

Date submitted: September 20, 2010
1. Introduction

Because of the clean, renewable and ample solar energy, researchers have been dedicating much effort to investigate how to effectively harvest the solar energy by solar cells of various types. Among various types of cells, dye-sensitized solar cells (DSSC) using nano-sized titania particles as photo-electrode material has its potential for practical applications. It is because of its reported more-than-10% efficiency and low manufacture cost. In the principal operation of DSSC (shown in Figure 1) the light absorption is performed by ruthenium complex dyes adsorbed on the surface of the TiO\(_2\) nanocrystalline film. When absorbing the sunlight, the dye molecules become excited and excited electrons are injected into the conduction band of titanium. The oxidized dyes can be reduced by the redox electrolyte (i.e., I\(_2\)/I\(_3^+\)) and the redox electrolyte can be also regenerated at the counter electrode coated with Pt. The whole process can take place continually to convert the sunlight into the electricity. One of parameters affecting the energy conversion efficiency of DSSC is the structure of TiO\(_2\) nanocrystalline photo-anode: the packing of TiO\(_2\) nanoparticles affects the electron transport and the porosity of TiO\(_2\) layer also decides the ionic diffusion path. Currently, screen printing is commonly employed for the preparation of such TiO\(_2\) layers. However, coating by screen printing usually creates the random packing of TiO\(_2\) nanoparticles and disordered (and possibly disconnected) ionic paths. It has been reported the continuous connection of TiO\(_2\) nanoparticles serves as the fast electron percolation paths while regularly arranged transport channels provides easy transport of dye and electrolyte within the nanostructure of TiO\(_2\). Further, the suitable pore size of the TiO\(_2\) particle film for the effective diffusion of the redox electrolyte is one of key factors affecting the cell efficiency.

Different assembly methods have been investigated in order to control the pore size and morphology of the TiO\(_2\) porous film used in dye-sensitized solar cells. For example, block copolymers were used as structure directing agent or constructing synthetic opals. TiO\(_2\) precursor was then filled into the porous copolymer film to produce the inverse TiO\(_2\) opal structure in the preparation of a 3D interconnected TiO\(_2\) layer. Several issues are often encountered in these methods: (1) on the inconsistency of the whole TiO\(_2\) film; (2) on the difficulty to make TiO\(_2\) films of larger area; and (3) on the difficulty in making TiO\(_2\) film on curved surface or 3D objects. Alternative solutions to the above-mentioned issues on the fabrication of TiO\(_2\) film are spray techniques, commonly done by inkjet printing. However, conventional spray techniques deliver
polydisperse droplets containing TiO₂ suspension (in the droplet sizes larger than 5 μm) onto conducting glass substrate, which have little control over the structure of TiO₂ film. To gain the great control on the formation of porous TiO₂ films with spray technique, the electrospray is thus proposed in our study.

The unique features of electrospray technique are that it produces monodisperse droplets with the sizes ranging from 10 nm to 4 μm and all the produced droplets are electrically charged to the same polarity. Because the electrospray produces monodisperse and highly-charged particles in the controllable sizes, the technique thus offers the great control over the formation of porous TiO₂ film at the both micro- and nano- scales. It offers the feasibility to fabricate the TiO₂ films with suitable pore sizes for different types of dye materials, such as organic dye and polymer dye. Further, nearly 100% sprayed material will be deposited on the electrode. It is because highly charged droplets can be directed to conductive surface by a designed electric field. At last, the mass throughput of electrospray can be further increased with the use of multiple or liquid sheet electrospray nozzles currently under the development in Chen’s laboratory.

In the present study, we proposed to use an electrospray system with two electric fields to control the deposition of TiO₂ nanoparticles. One electric field is used to produce monodisperse droplets and the other used to control the packing of these droplets via the control of droplet impaction velocity. We had performed a comprehensive study of the factors that influencing the formation of TiO₂ film. It was found that the pore size could be adjusted by controlling the electric field, which consequently determined the packing density of the TiO₂ film.
We further characterized the properties of these electrosprayed-TiO$_2$ films and the performance of dye-sensitized solar cells. For the comparison, we also characterized the TiO$_2$ film prepared by screen printing method in this study.

2. Fabrication of TiO$_2$ film by electrospray

2.1 Preparation of TiO$_2$ paste

Two kinds of TiO$_2$ pastes were prepared in our study: one is for compact TiO$_2$ layer and the other is for mesoporous TiO$_2$ film. In the DSSC, the electrolyte ($\Gamma/\Gamma_3^-$) has a strong over-potential at the interface between the fluorine doped SnO$_2$ (FTO) anode and the electrolyte, so that a barrier exists to prevent the photo-generated charges from recombination at the boundary. Employing a compact TiO$_2$ layer between the fluorine doped SnO$_2$ (FTO) anode and the electrolyte can reduce charge recombination losses and further improve the cell efficiency [Burke, A. et al., 2008]. The mesoporous TiO$_2$ film is for the electrode where the dye will be placed. The following are the recipes for the preparation of such pasts:

(a) TiO$_2$ past for compact layer

- **Solution A**: 1 ml Titantium isopropoxid / 10 ml Etanol
- **Solution B**: 1 ml HNO$_3$ / 10 ml Etanol

3 ml Solution B was added into Solution A and reacted under 40 °C 30 min to form the transparent white solution containing nanosize TiO$_2$ particles

This TiO$_2$ paste was spin-coated on a cleaned fluorine-doped tin oxide (FTO) glass and sintered at 200 °C 30 min to form the transparent compact layer

Figure 2. (a) TiO$_2$ paste for preparing compact layer. (b) TiO$_2$ compact layer coated on the FTO glass.
2.2 Preparation of mesoporous TiO$_2$ film

Two different methods were used for the preparation of mesoporous TiO$_2$ film:

(a) Screen printing

3M tape was used as a spacer and about 0.1 ml TiO$_2$ paste was dropped on the one side of FTO glass. A glass rod was applied to roll over the FTO glass and spread the TiO$_2$ paste to form the TiO$_2$ film. After the evaporation of solvent, this TiO$_2$ film was sintered at 450 °C for 30 min.

(b) Electrospray

Shown in Figure 3 is the schematic diagram of electrospray system for depositing the TiO$_2$ nanoparticles onto the FTO glass. The TiO$_2$ paste was fed through a nozzle by a syringe pump. A spray electrical field was established between the nozzle and metal stabilization ring.
with positive high voltage on the spray nozzle and electrically grounding on the metal ring. By applying sufficient high voltage on the electrospray nozzle, the stable cone-jet was formed at the nozzle exit to produce monodisperse TiO₂ droplets (shown in Figure 4). With the control of suspension liquid feed flowrate and the conductivity of the spray suspension, the droplet size could be controlled form micro- to nanometer sizes. In our setup an auxiliary negative electrical field is further established between the stabilization ring and FTO glass. Electrospray-produced monodisperse droplets were then accelerated or decelerated in the auxiliary electrical field. Droplets with variable impaction velocity can be controlled by the strength of the auxiliary field and consequently the packing of TiO₂ particle structure on the FTO substrate. This technique can provide effective and facial method to control the packing density and porosity of TiO₂ film. After the deposition of TiO₂ particles, the TiO₂ film was also sintered at 450 °C for 30 min.

Figure 3. A schematic diagram of the electrospray system for the fabrication of TiO₂ film.
2.3 Characterization of solar cells

The prepared different TiO$_2$ films were soaked in the N3 dye/ethanol solution 24 h to absorb the N3 dye. 0.5 M LiI, 0.05 M I$_2$, and 0.5 M t-butylpyridine in acetonitrile was used for the electrolyte. The Pt/FTO glass was used as a counter electrode and a plastic sheet was inserted between the FTO/TiO$_2$ and FTO/Pt electrode as the spacer. Electrolyte was inserted in the cell and the cell was sealed.

3. Results and Discussion

3.1 Control of the TiO$_2$ layer porosity by electrospray with auxiliary electric field

Auxiliary negative electrical fields with 3, 6, and 9 kV were studied to create different deposition density. Figure 5 shows the SEM images of the TiO$_2$ films prepared by screen printing and electrospray with different deposition rates. The TiO$_2$ film made by screen-print method is densely packed. For the TiO$_2$ film prepared by electrospray, the packing density increases with the auxiliary negative electrical field. In the screen printing method, the porosity of TiO$_2$ film is in general dependent on the packing of TiO$_2$ nanoparticles. In some cases, polymers were also used in TiO$_2$ pastes to make appropriate spacers for ionic diffusion. By using electrospray deposition, both the porosity and ion-diffusing path of TiO$_2$ film can be tunable via adjusting the suspension feeding flowrate to vary the droplet size and the auxiliary negative electrical fields to control the layer packing density.
Figure 5. The SEM images of TiO\textsubscript{2} films fabricated by screen printing and electrospray with different deposition voltages: (A) screen printing (B) 3 kV (C) 6 kV (D) 9 kV.

BET data (given in Table 1) shows the surface area and the porosity of the TiO\textsubscript{2} film fabricated by electrospray. The porosity of TiO\textsubscript{2} films prepared by electrospray increases with the increase of auxiliary deposition voltage in general. Further note that all the films prepared by electrospray has higher surface area than those prepared by screen printing.

We used two different dyes (shown in Figure 6) to test the absorption ability of these films: one is cis-di(thiocyanato)-N,N’ 6-bis (2,2’ –bipyridyl-4,4’-dicarboxulato) ruthenium (II) (N3 dye) as a small molecule dye and the other one conducting polymer, polyaniline as a large molecule dye. The absorption amount of N3 dye for these electrosprayed films is in general higher than that of the film prepared by screen printing. It is because electrosprayed films have higher surface areas than those prepared by screen printing. However, for the conducting polymer, polyaniline, the absorption amount decreases with the increase of the auxiliary deposition voltage. Since the polymer has larger hydrodynamic volume than that of N3 dye, it is not easy for the polymer to penetrate the TiO\textsubscript{2} film with small pore sizes. The films prepared
with low auxiliary deposition voltage of 3 and 6 kV have large pore sizes, which makes the absorption of polymers easy.

The above result evidences the electrospray technique offers a feasible way to prepare specific structures of TiO₂ film for various dyes.

Table 1. The BET measurements and the absorption of organic dye and polymer dye.

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Surface area (m²/g)</th>
<th>Pore size (nm)</th>
<th>Porosity</th>
<th>N3 absorption (M dye/g TiO₂)</th>
<th>Polyaniline absorption (M polymer / g TiO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>81</td>
<td>50</td>
<td>0.532</td>
<td>3.5*10⁻³</td>
<td>3.0*10⁻⁵</td>
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<tr>
<td>6</td>
<td>93</td>
<td>27</td>
<td>0.686</td>
<td>8.7*10⁻³</td>
<td>1.7*10⁻⁵</td>
</tr>
<tr>
<td>9</td>
<td>119</td>
<td>19</td>
<td>0.748</td>
<td>1.4*10⁻²</td>
<td>2.0*10⁻⁶</td>
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<tr>
<td>Screen print</td>
<td>79</td>
<td>16</td>
<td>0.621</td>
<td>2.5*10⁻³</td>
<td>4.5*10⁻⁶</td>
</tr>
</tbody>
</table>

3.2 V<sub>oc</sub> decay & electron lifetime

Since the electron-transfer kinetics in the TiO₂ film also play an important role in the efficiency of DSSCs, the electron lifetime (τ<sub>n</sub>) as a function of open-circuit potential (V<sub>oc</sub>) for electrosprayed TiO₂ films were characterized with the V<sub>oc</sub> decay technique. The same investigation was also performed for the screen-printed TiO₂ film for comparison. In this comparison, the thickness of all films was kept at 8 μm. The value of V<sub>oc</sub> was recorded against the measuring time when the illumination state was changed to the dark. The electron lifetime τ<sub>n</sub> can be related to the V<sub>oc</sub> decay derived from the Equation (1):

\[
\tau_n = -\frac{k_B T}{e} \left( \frac{dV_{oc}}{dt} \right)^{-1}.
\] (1)
where, $k_B T$ is the thermal energy, $e$ the positive elementary charge, and $dV_{oc}/dt$ the time derivative of $V_{oc}$. The resulted $V_{oc}$ decays for electrosprayed TiO$_2$ films and screen-printed film is shown in Figure 7. The decays indicate that the screen-printed TiO$_2$ film has much quicker decay in $V_{oc}$ than that of electrosprayed films. The observation infers that electrosprayed TiO$_2$ films provides more superior environment for fast charge transport and low electron recombination characteristics.

![Figure 7](image)

**Figure 7.** $V_{oc}$ decay of the electrosprayed TiO$_2$ films and the screen-printed film when the illumination state was changed to dark.

Figure 8 shows SEM images of the cross-section of TiO$_2$ films prepared via electrospray and screen printing. The images indicate the packing of the TiO$_2$ particle layer prepared via the screen printing is compact and dense. The electron transport and ion diffusion in this 3D packing of the screen-printed TiO$_2$ film would be random and sometimes confined in some areas. However, the TiO$_2$ particles in electrosprayed films are upward-growing packed. This upward-growing packing can provide the perpendicular channels form the bottom to the top for the redox
I\textsuperscript{-}/I\textsubscript{3}\textsuperscript{-} ions diffusion, which may result in more efficient electrolyte-dye interaction. Further, the organized packing of the electrosprayed film may speed up the charge transport and ion diffusion because of the geometric confinement. This may also explain why the \( V_{oc} \) decay was slower in electrosprayed films. Since it has been found that the charge collection efficiency of the cells can be improved by promoting fast charge transport and ion diffusion we thus conclude that TiO\textsubscript{2} films prepared by electrospray may have better cell performance than that prepared by screen printing.

**Figure 8.** The the cross-section images of the TiO\textsubscript{2} films prepared by the screen-print method (A) and the electrospray deposition (B).

Further, it is worth noting in this report that the \( V_{oc} \) decay of electrosprayed films with low accelerating deposition voltage is slower, which may indicates the film prepared with accelerating deposition voltage of 3 kV has suitable pore size for ion diffusion.

Since the accelerating deposition voltage can be used to control the packing density, it
makes possible to prepare TiO$_2$ film with various porosities. We had built up the TiO$_2$ layer with the increase of pore size in the film depth by controlling the accelerating deposition voltage during the spray process. The SEM image of the cross section of above prepared film is given in Figure 9. Also given in Figure 9 is the $V_{oc}$ decay characterization of such variable porous film. The measured decay curve shows that the rate of $V_{oc}$ is slower than that of electrosprayed films with single porosity. We believe that the above result is attributed to the large pores close to the film surface, allowing more effective ion diffusion to reduce the oxidized dye, and the small pores near the film base, minimizing the recombination of photoexcited electrons with the I$_3^-$ ions.

Figure 9. The cross-section image and the $V_{oc}$ decay of the electrosprayed film with composite porosity.
4. Conclusion

The electrospray deposition technique can provide a flexible way to fabricate TiO$_2$ films with controllable structure for sensitized solar cells. Our preliminary results show the TiO$_2$ film prepared by electrospray has better cell properties than that prepared via common screen-printing method. More, the studied electrospray method has the potential to prepare the TiO$_2$ mesoporous films on the plastic or curved substrates.

5. References:

Activities and Final Results of MAGEEP funded Pilot Research (2009-10):

Title: “Coastline loss and the socio-environmental impact of displaced communities: Correlating environmental catalysts for shoreline change with human responses”

Budget: $10,000
Duration: 9/2009-9/2010
PI: Dr. Michael Frachetti
Co-PI: Dr. Patrick Daly

Goals and activities to date:

The pilot phase of this research was focused on the assessment of the contemporary state of environmental impact on the Island of Nias and on determining the availability of data sources and their analytical efficacy for facilitating the proposed research. In November 2009, our team carried out a two-week visit to Nias to establish viable study sites and ground truth the issues described above.

Results of the pilot visit to Nias:

The island of Nias and its inhabitants have been considerably affected by the environmental changes resulting from both the 2004 tsunami and 2005 earthquake. Although nearly all of the aid groups have closed operations on Nias, local villagers are still heavily engaged in new strategies for coping with the altered shorelines and coastal ecology in the aftermath of the 2005 earthquake.

Traveling to Nias resulted in the identification of two study sites suitable for intensive analysis. The first study site is the town of Afulu, whose beaches extending along the Northwestern coastline to Lahewa, where tectonic uplift significantly extended the coastal geography. In Lahewa, the uplift elevated a major trade port and fishing dock, which today has been rebuilt. In the more rural sectors of Afulu, new beaches and exposed reefs have caused a variety of shifts in fishing practices, as well as expanding agricultural practices. The ecological impacts observed along the Northwest coastal sites of Afulu/Lahewa during our visit include:

- Uplift causing more than 200m of new beach front
- Overgrowth of new territory, government seizure of new land
- Impact on reef ecology
  - Reduction of apex predators (sharks)
  - Overfishing of extant reef
- Sand extraction and coral collection from new beaches

At the second identified study site, Bozihona (located on the SE coast) the geological subsidence had more drastic ecological effects. Bozihona lost nearly 500m of shoreline,
and the entire village was reconstructed in areas which were previously jungle. In Bozihona, we observed the following changes in the ecology and practices of local villagers:

- 25-50 hectares of coconut palms destroyed
- Village has been rebuilt 1km back from the shore
- Intensive gardening has transformed immediate vegetation, while the selection of crops has transitioned to faster yield cash crops, rather than established commodities such as coconuts
- Salinization of river impacts water use
- Loss of pasture

These observed changes significantly guide our perspective on the cumulative impacts of environmental changes in these case studies, and provide substantial cases for analyzing how development efforts and local strategies have together reformed these villages.

Current activity

With these appropriate sites identified, our energy throughout the spring of 2010 was devoted to developing a working digital platform to begin more detailed analysis in GIS. Work in the SAIE laboratory was oriented around digitizing and compiling openly available data to assess quantitatively the degree of coastal change. The result of these efforts has been positive, but has also illustrated that the free, low-resolution data currently available is not appropriate for the level of analysis required. Thus, although not enabling us to carry out the necessary analysis at this stage, our initial modeling and mapping in GIS has illustrated that more nuanced approaches will be successful for achieving the proposed goals of the project.

We have made steady progress in developing an international and multi-disciplinary team of colleagues interested in growing this project. In addition to the co-PI, Dr. Patrick Daly, Dr. Kerry Sieh of the Earth Observatory of Singapore at Nanyang Technical University has agreed to promote our project through future collaboration, as his work addresses similar issues of sustainability in human/environmental relationships, although from an earth sciences perspective. He has agreed to share data, which he has collected over the past decade working in SE Asia, and has encouraged possible opportunities for funding or cost sharing between our institutions. Recently, other potential members of the larger project initiative have been identified, including Dr. Barbara Schall from the Biology Department at Washington University in St. Louis. Dr. Schall may participate in the phase 2 field work of this project, incorporating her expertise in rice genetics to understand potential genetic transformations in the rice breeds cultivated across the agricultural sector of Nias.

The spring of 2010 was also devoted to applying for continuing funding, specifically to acquire high-resolution imagery, which is the fundamental step to move this project to the next phase. A grant in the amount of $35,000 was proposed to the I-Cares research board but was unsuccessful in the first application. At present, we have submitted other funding requests to the Geoeye foundation for satellite imagery, and anticipate a number
of funding requests to the National Geospatial Agency and NASA – which have annual deadlines for funding in the fall of 2010. Thus, at present we are working to secure future funding and to grow the international collaboration through publicity and professional lectures.

Dr. Frachetti has made three presentations of the Nias ecology project at both Washington University in St. Louis and to the National Geospatial Agency. In addition, we have launched a project webpage within the scope of the PI’s laboratory website:


These efforts are drawing attention of future collaborators and funding agencies – as evidenced by a recent invitation by the US government to participate in a poster presentation at the NGA history museum highlighting the use of digital technology in human geography and sustainability. In addition, the efforts of the SAIE laboratory have been recently recognized by international academic publishers at Cambridge University Press. Dr. Frachetti has been invited to contribute a monograph concerning “Digital Methods in Archaeology” – in part spurred by research such as the Nias digital ecology project. We are hopeful that our research team will secure a second round of funding to continue our project in the near future, and expect that in due time we will be able to apply for a multi-disciplinary and large scope program of research with a collaborative scientific team.
Figures and Appendices:

NW coasts experience significant uplift, i.e. New Beaches and exposed reef

Figure 1. Effects of the 2005 Nias earthquake on the western side of the island (photo, K. Sieh).
Figure 2: Effects of the 2005 Nias earthquake on the eastern side of the island (upper photo illustrates the study site, Bozihona in 2005 (photo, K.Sieh).
Figure 3: Preliminary shoreline analysis using 30 m resolution Landsat TM images, deformation of SE coastline, Nias Indonesia. (M. Frachetti)
Abstract
Our international team investigated the principles and performance of electrocoagulation treatment systems for the removal of arsenic from drinking water. High arsenic concentrations in drinking water are serious public health issues in India, the United States, and many other countries. Sustainable technologies for treatment of arsenic-containing water are needed for small communities in the developing world, and electrocoagulation is a promising method for such communities. We integrated treatment process evaluation, aquatic chemistry modeling, and molecular-scale characterization to identify the impact of water chemistry on treatment performance and to elucidate the mechanisms of arsenic removal. Batch electrocoagulation experiments were performed in the laboratory using iron electrodes. The experiments quantified the effects of pH, initial arsenic concentration and oxidation state, and concentrations of dissolved phosphate, silica, and sulfate on the rate and extent of arsenic removal. Arsenic removal was slower at higher pH. When solutions initially contained As(III), a portion of the As(III) was oxidized to As(V) during electrocoagulation. The presence of 1 and 4 mg/L phosphate inhibited arsenic removal, while the presence of 5 and 20 mg/L silica or 10 and 50 mg/L sulfate had no significant effect on arsenic removal. As(V) adsorption, including competitive adsorption with phosphate, was successfully modeled as a function of pH. An overall model for the electrocoagulation process was developed. For most conditions examined in this study, over 99.9% arsenic removal efficiency was achieved.

INTRODUCTION AND BACKGROUND

Arsenic in Drinking Water
Arsenic is a toxic and carcinogenic element that can be found at high concentrations in groundwater. High arsenic concentrations are usually from natural sources in soils and rocks, although human impacts on hydrogeochemistry can cause increases in concentrations (Harvey et al. 2002). In the United States, the maximum contaminant level for arsenic in drinking water was lowered from 50 to 10 μg/L in 2001, and many small communities that rely on groundwater for their drinking water supply were impacted by this change in the standard (U.S.EPA 2001). While arsenic in drinking water is a concern in the United States, the most serious arsenic impacts on public health are occurring in Bangladesh and in West Bengal, India, where concentrations can exceed 1000 μg/L (Smedley and Kinniburgh 2002).

Technologies for Arsenic Treatment in Small Communities
Technologies based on arsenic adsorption to iron oxides and hydroxides can remove arsenic from water with high efficiency and relatively small footprints. In these treatment systems, dissolved arsenic
partitions to the surface of the solid iron (hydr)oxide, which either is already immobilized or is easily removed by settling or filtration. The iron hydr(oxides) have very high ratios of surface area to mass, and their surfaces have high affinities for binding arsenic. Arsenic can occur in two oxidation states in groundwater, As(V) (arsenate) and As(III) (arsenite); while both As(III) and As(V) can be removed by iron (hydr)oxide-based processes, removal of As(V) is usually more efficient (Hering et al. 1996). Iron (hydr)oxide sorbents have been studied in column and batch experiments for potential use in drinking water treatment (Badruzzaman et al. 2004, Gu et al. 2005, Zeng et al. 2008a).

Electrocoagulation is a treatment process that uses arsenic adsorption to iron hydr(oxides) but has several key differences to conventional coagulation and sorbent methods. Instead of supplying the iron hydr(oxide) directly or generating it from chemical coagulants, which can be difficult to distribute and handle, the iron (hydr)oxide is generated in situ by precipitation of iron(III) released from one of the two iron electrodes used in electrocoagulation (Figure 1). The deployment of electrocoagulation for small communities requires fewer materials for distribution and can use electricity from a transmission grid, a battery, or an on-site renewable source (e.g., solar photovoltaic).

Water chemistry strongly impacts the adsorption of arsenic to iron (hydr)oxides. Adsorption of As(V) decreases with increasing pH over an environmentally-relevant pH range (Zeng et al. 2008b). Dissolved phosphate and silica, which are often present in groundwater at high concentrations, can inhibit arsenic adsorption through competition for binding sites on the iron hydr(oxide) (Hiemstra and Van Riemsdijk 1999, Zeng et al. 2008b). Silica may also polymerize at the surface to block binding sites (Davis et al. 2002). Molecular-scale characterization of arsenic-loaded iron (hydr)oxides can provide further insights into the mechanism of removal and the structure and oxidation state of the arsenic on (or in) the iron (hydr)oxide.

**Project Objectives**

The overarching project objective was to advance the understanding of the electrocoagulation process to enable its optimal deployment for water treatment. Specific objectives were to:

- Quantify the impacts of water chemistry on the efficiency of arsenic removal by electrocoagulation.
- Develop reaction-based models that can predict the performance of electrocoagulation.
- Integrate analysis of the aqueous phase with direct characterization of the solid phase to elucidate the mechanisms of arsenic removal in the electrocoagulation process.
- Build a productive research collaboration between Washington University and the Indian Institute of Technology – Bombay for studying sustainable technologies for water treatment.

**Figure 1.** Overview of research on arsenic removal from drinking water using electrocoagulation. The project integrated expertise from three departments at two universities.
Materials and Methods

Electrocoagulation Experiments

The laboratory-scale electrocoagulation reactor consisted of a 1 L glass beaker with two iron rods immersed in the aqueous solution. The rods had diameters of 1.75 cm, lengths of 20 cm, and were placed 2 cm apart in the arsenic containing solution. A voltage of 12 V was applied to the terminal electrodes for two hours from a direct current power supply. To provide enough oxygen for the formation of Fe(III) precipitates, the solution was sparged with air at a flow rate of 60 mL/min. The arsenic containing solution was magnetically-stirred (200 rpm). The treatment process was evaluated for aqueous solutions with pH 5-9, two arsenic concentrations (100 and 1000 µg/L), both As(III) and As(V), and the presence of dissolved phosphate, silica, and sulfate as potentially inhibitory species. All solutions were prepared with ultrapure water and desired volumes of stock solutions.

At predetermined sampling times from 5 to 120 minutes, 15 mL of solution was collected from the beaker. Of this amount, 7.5 mL was filtered (0.45 µm polyethersulfone membranes), and the filtrate was acidified to 1% HNO₃. Another 7.5 mL of unfiltered suspension was acidified to 1% HNO₃, which completely dissolved the suspended solids. For the experiments using As(III), an additional sample was collected for arsenic redox speciation (i.e. separation of As(III) and As(V)) using an anion-exchange method (Wilkie 1997). Before separation, the pH of a 10 mL aliquot of filtered solution was adjusted to around 3.5 and then passed through a column containing anion exchange resin. At the end of each experiment, 15 mL of unfiltered suspension was collected for zeta potential measurement. The remaining settleable solids were collected and freeze-dried in preparation for solid-phase characterization. The filtered and acid-treated samples from the laboratory experiments were analyzed for dissolved and total concentrations of arsenic, iron, phosphorus, and silicon. The specific surface areas (SSA) of the solids were measured by the BET N₂-adsorption method. X-ray powder diffraction (XRD) patterns were collected using Cu Kα radiation. Zeta potential was measured by a nanoparticle characterization instrument with zeta potential capability.

The results of the laboratory experiments were compared with the performance of electrocoagulation systems measured as part of a previous field study. The field test units consisted of a 50 L plastic bucket, a 12 V direct current source with a rating of 2 A, two iron plates (10 cm by 15 cm with a submerged depth of 10 cm), and an aquarium pump with a diffuser. The iron plates were separated by a distance of 0.5 cm and were connected to a support that fixed them in place with a non-conductive PVC screw. The electrocoagulation system was followed by a common ceramic candle filter assembly (average pore size of 1 µm) for the removal of suspended particles. Field trials for the electrocoagulation system were carried out in a village in the Nadia district of West Bengal. The village chosen for the field trials was Ghetugachi, which falls under Chakdaha block. The average arsenic level was found to be 400 µg/L, and the phosphate levels in the groundwater were also high. Ghetugachi was selected for the field trials because a predominance of As(III) and the high phosphate concentrations presented a challenging scenario for arsenic removal. A total of 17 electrocoagulation systems were distributed in Ghetugachi and evaluated after one week of use by the households.

Arsenic Adsorption

Equilibrium adsorption of As(V) to the solids generated during electrocoagulation was investigated in batch experiments as a function of pH and the concentrations of As(V) and phosphate. Since As(V) adsorption may be far from equilibrium during electrocoagulation, the iron oxides for batch experiments were first generated by electrocoagulation in the absence of arsenic and then they were equilibrated with arsenic in batch suspensions. The electrocoagulation reactor was operated without As at pH 7 for 2 hours to generate enough iron oxide for adsorption experiments. Experiments to generate data for an adsorption isotherm at pH 4 used a stock iron oxide suspension and aliquots of As(V) stock solution to provide a wide range of total As(V) concentration. The pH dependence of As(V) adsorption
was determined in similar experiments with a fixed 100 µg/L or 1000 µg/L As(V) concentration over a pH range from 4 to 10. Experiments to study the pH-dependence of adsorption were performed both with and without 1 or 4 mg P/L of phosphate.

Results

Performance of Electrocoagulation Process as a Function of Water Chemistry

The removal rate of arsenic was affected by the pH (Figure 2). For experiments using 100 µg/L As(V), it took less than 30 min for the dissolved As(V) concentrations to drop below 1 µg/L at pH 5, 6 and 7. At pH 8, the dissolved As(V) concentration only reached this value after 75 min, and at pH 9 the dissolved As(V) concentrations remained at 4 µg/L after 120 min. Although As removal was slower at higher pH, the final removal efficiency was independent of pH from 5 to 8. The iron oxyhydroxide produced in the reactor was identified as lepidocrocite (γ-FeOOH) by XRD analysis. The only exception to lepidocrocite formation was the production of an amorphous ferric hydroxide when dissolved silica was present. The specific surface area of the lepidocrocite was 200 m²/g. Once sufficient lepidocrocite was produced to provide adsorption sites for As, low dissolved As concentrations could be obtained.

As(V) removal was usually faster than As(III) removal. In all the experiments using As(III), the dissolved As(V) concentration increased first and then decreased with increasing reaction time. The increase in As(V) when treating As(III) solutions indicated that at least 25% of the As(III) was oxidized to As(V) during electrocoagulation. The removal mechanism for As(III) by electrocoagulation was proposed to be the oxidation of As(III) to As(V) followed by adsorption of As(V) to the iron oxides (Kumar et al. 2004). As(III) oxidation to As(V) has previously been proposed to occur with dissolved oxygen and soluble intermediates in Fe(II) oxidation acting as rate-enhancing species (Ciardelli et al. 2008, Sahai et al. 2007). As(III) oxidation can also occur when Fe(II) is present with Fe(III) oxyhydroxides, and the mechanism has been proposed to involve the formation of reactive iron intermediate species (Amstaetter et al. 2010, Bisceglia et al. 2005).

The presence of 1 mg/L and 4 mg/L phosphate as P inhibited the removal of As (Figure 3). The inhibitory effect was more significant at higher phosphate concentrations. Considerable phosphate was also removed during the electrocoagulation, which indicates that phosphate can compete with As species for the surface sites of lepidocrocite. Competitive adsorption of phosphate with As(V) agrees with the results of previous studies (Meng et al. 2002, Zeng et al. 2008b). The inhibitory effect of phosphate on As removal during electrocoagulation may also be caused in part by the slower oxidization of Fe(II) to Fe(III) in the presence of phosphate, which can decrease the rate at which the sorbent is formed.

![Figure 2. Dissolved As(V) concentrations during electrocoagulation of solutions initially containing 100 µg/L As(V). The data points for pH 5 are partially obscured by those for pH 6.](image-url)
The presence of 5 and 20 mg/L dissolved silica had no significant effect on As removal, even though considerable silica was removed during the electrocoagulation process and silica prevented the formation of lepidocrocite. Meng et al. (2002) also observed no significant effects of silica on As(V) adsorption to iron hydroxides when silica was present at concentrations as high as 36 mg/L. In a separate study, Davis et al. (2001) observed silica inhibition of As(V) adsorption to ferric hydroxide, but only when silica and ferric hydroxide had been prequilibrated for 50 days; at shorter contact times, there was much less inhibition.

Almost all of the field units were able to lower arsenic concentrations to below 10 µg/L after electrocoagulation, settling, and candle filtration. For the small number of systems that were unable to achieve 10 µg/L, visits to the households determined that the units were not being operated as per the instructions provided. The untreated waters had very high arsenic concentrations, in the range of 400-700 µg/L, and most also had high phosphate concentrations. Despite the high initial concentrations, most final filtered water samples had arsenic concentrations less than 10 µg/L, and the phosphate concentrations in treated waters were below the detection limit of 0.5 µg/L. While significant removal of arsenic occurred with electrocoagulation followed by settling, the filtration step led to further decreases in the arsenic concentration. No inhibition of treatment performance from phosphate was observed in the field trials. The systems with the highest phosphate concentrations had settled and filtered water

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Figure 3. Dissolved (a) phosphate (in mg P/L), (b) dissolved As(V), and (c) total (closed symbols) and dissolved (open symbols) iron concentrations during electrocoagulation of solutions initially containing 100 µg/L As(V) at pH 7.
concentrations that were comparable to those from the other properly operated systems. The electrocoagulation treatment time for the field trials was selected to produce sufficient iron oxide coagulant to remove both As and phosphate, so it is not surprising that no effect of phosphate was seen in these trials.

**Arsenic Adsorption and Overall Performance Modeling**

The As(V) adsorption density on the iron oxyhydroxide produced by the electrocoagulation reactor increased with increasing dissolved As(V) concentration until a saturation level was reached. As(V) adsorption decreased with increasing pH from 4 to 10 at total As(V) concentrations of 100 and 1000 µg/L (Figure 4a). The pH-dependence of adsorption was interpreted using a surface complexation model with the diffuse double layer to account for electrostatic contributions to adsorption. The pH-dependence of As(V) adsorption could be described very well for both 100 and 1000 µg/L total As(V) using the model. The surface complexation constants for As(V) adsorption were systematically varied using the computer program MINEQL+ 4.6 (Schecher and McAvoy 2007) to obtain the constants that provided the best fit of the model to the experimental data. The equilibrium constants reported by Dixit and Hering for the formation of As(V) surface complexes on hydrous ferric oxide were used as the starting points (Dixit and Hering 2003), and the optimal values for the lepidocrocite were similar to these

![Figure 4](image-url)

**Figure 4.** Equilibrium adsorption to lepidocrocite of As(V) in the (a) absence and (b) presence of phosphate as a function of pH. Data are presented as points and the surface complexation model simulations are shown as lines. In panel a data are shown for initial As(V) concentrations of 100 (■) and 1000 µg/L (●). In panel b adsorption of 100 µg/L total As(V) is shown in the absence of phosphate (■) and in the presence of 1 (●) and 4 (▲) mg P/L of phosphate.
starting values. Phosphate can compete with As(V) for adsorption sites. The presence of 1-4 mg P/L of phosphate inhibited As(V) adsorption (Figure 4b). The addition of 1 mg P/L phosphate can decrease As(V) adsorption by more than 60%, and 4 mg P/L can decrease As(V) adsorption by nearly 90%.

In the electrocoagulation process, the rate of As(V) removal can be assumed to be proportional to the difference between the actual and the equilibrium dissolved concentration of As(V) (i.e. the driving force) and the amount of solid lepidocrocite present. An overall model for the reactor performance was constructed by considering the rate of production of the sorbent (the iron oxyhydroxide lepidocrocite) and the rate of As(V) adsorption. The kinetic model simulated As(V) removal by electrocoagulation well. The As(V) removal rate was slower at higher pH during electrocoagulation. A similar pH effect was observed by Thella et al., who found that the arsenic removal rate decreased with increasing pH from 2 to 8 (Thella et al. 2008).

CONCLUSIONS AND ENVIRONMENTAL IMPLICATIONS

Arsenic removal by electrocoagulation involved lepidocrocite formation followed by arsenic adsorption. Removal was slower at higher pH and higher initial arsenic concentrations. As(III) was partially oxidized to As(V) during electrocoagulation. As(V) removal was faster than As(III) removal. Phosphate inhibited As removal by acting as a competing adsorbate and possibly by delaying the oxidation of Fe(II) to produce lepidocrocite. Although silica prevented the formation of lepidocrocite, arsenic removal was still very rapid and extensive by adsorption to the amorphous iron oxides that formed. Sulfate had no significant effect on As removal or coagulant formation. Over 99.9% arsenic removal efficiency could be achieved in both the laboratory experiments and the field trials. The field trials indicate that electrocoagulation has the potential to treat arsenic-contaminated water to standards required for drinking water.

As(V) adsorption onto the iron oxyhydroxide generated by electrocoagulation and competitive adsorption of As(V) and phosphate over a wide pH range were successfully simulated by a surface complexation model. The model can be used to predict As(V) adsorption based on the water chemistry over a wide range of conditions. The surface complexation modeling approach can be used to assess the potential performance of electrocoagulation for arsenic removal for various waters without needing to conduct lengthy experiments. An overall rate model could simulate As(V) removal during electrocoagulation by accounting for the rates of coagulant production and arsenic adsorption. Such a model can be used as a design tool for predicting As(V) removal by electrocoagulation for different reactor configurations.

PLANS TO CONTINUE COLLABORATION

The project team will continue collaborating on specific activities in the near-term and will seek research support for long-term collaboration. Faculty visits have been critical to this project. The idea for this project grew out of discussions between Professors Giammar and Chaudhari when Giammar visited IIT Bombay in December 2008. Once the project was awarded, Giammar visited IIT Bombay again in January 2010 for discussions with Chaudhari and to work with one of his Ph.D. students on studying the electrocoagulation reactor used at IIT Bombay and to teach the student an aqueous chemical equilibrium program. Chaudhari will visit Washington University in October 2010. Although the current funding and project period have been completed, selected experiments that are targeting the mechanisms of As(III) oxidation during the process are continuing in Giammar’s laboratory. Giammar and Chaudhari will continue to consult with one another on their research on arsenic treatment processes.

The project team will seek resources to support the continued collaboration. Future projects can continue studying processes for treatment of arsenic-containing water sources, and they may also expand into additional areas of mutual interest in drinking water treatment. If available, the project team will seek continued support from the McDonnell Academy Global Energy and Environment Partnership.
collaborative research on arsenic formed a key element of a well-reviewed but unsuccessful proposal to the National Science Foundation Integrated Graduate Education, Research, and Training (IGERT) program that was focused on interfacial processes in aquatic systems. The collaborative program with IIT Bombay that was included in the proposal was very favorably reviewed. This proposal will likely be resubmitted next year. The oxidation-reduction processes involved in the process also served as the basis for a pending proposal by Giammar, Catalano, and Cynthia Lo to the Dreyfus Foundation Postdoctoral Program in Environmental Chemistry. Should this proposal be successful, then Giammar, Catalano, and Lo will co-mentor a postdoctoral researcher in the study of arsenic reaction mechanisms on iron oxide surfaces, and the researcher will be encouraged to visit Chaudhari IIT Bombay as part of the project. In addition to the IGERT and Dreyfus Foundation proposals, support for the research may be sought through proposals to the National Science Foundation program in environmental engineering and to the Water Research Foundation.

**RESEARCH PRODUCTS RESULTING FROM WORK**

The project has formed the basis for one manuscript submitted for publication and another that is currently in review:


The project results were also presented at the Spring 2010 meeting of the American Chemical Society:


**REFERENCES CITED**


The Center for New Institutional Social Sciences [SNISS] was granted a research grant from MAGEEP on May 2009 of the amount of $15,000. The grant was given to the center to help its initiative of introducing social sciences into the debate on alternative strategies for the implementations of Diversified Energy Production Strategies [DEPS]. The main premise behind the initiative is that institutions often matter at least as much as market forces and technology in the deployment, or lack thereof of DEPS. With alive and kicking Nobel Laureate in Economics (1993), Professor Douglass C. North, as our inspiration, CNISS has offered to pursue a systematic research agenda to explore the role of formal and informal institutions in the deployment of DEPS. As soon as we got the grant we immediately got off on a very strong start. We have been able to secure a matching grant of 9 K from I-CARES in April of 2010. We then teamed up with a group at the University of Minnesota Carlson Business School a group at the Recanati Business School at Tel Aviv University and received another grant of 75 K from the Minnesota based IREE – Initiative for Renewable Energy and the Environment on July 2010, of which our share is $25,000. We presented findings of this research as the Conference for Green Economy in Minnesota in the spring (April 2010), at the undergraduate research symposium at WU in May (2010), at the AOM in Montreal in the summer (August 2010) and were invited to present more findings at the Israeli Strategy Conference in December of 2010, in Haifa. We will present a poster at our own quickly approaching MAGEEP annual symposium in October of 2010. What follows is a summary of our findings so far.

INTRODUCTION

With the menace of climate change looming over the world’s shoulder, and with disasters such as the 2010 Deep Horizon oil spill along the Gulf coast of the southern U.S. plaguing natural ecosystems and livelihoods, adopting clean alternative energies has become more important than ever before. What drives the adoption of these energies, however, has yet to be fully determined. While some, namely neoclassical economists, suggest it is simply a matter of reducing regulation and promoting free markets (so that resource scarcity would drive alternative energy deployment), others have posited that technology alone will propel the use of alternative energies. Further complicating the issue, the Neo-Institutional School of Social Science submits that market forces lead to institutional changes (North, 1990) and at the same time politically motivated changes in institutional structures dictate progress or lack thereof in economic markets (Sened, 1997), creating a cyclical argument that is difficult to tie to any exogenous variables that may serve as explanation in a causal model of the process. Considering this confusion and contemporary energy related crises, extricating the roles of resource availability, technology, and institutions in driving alternative energy utilization would greatly improve our ability to understand the forces and realities behind the global task of effectively and efficiently embracing and utilizing clean energy resources to fuel the global economy.

Given the complexity of the energy production sector and the institutional structure that surrounds it, we consider the state of wind power technology via cost comparisons to other electricity sources (e.g. coal power plants). By focusing on one of the most advanced and currently popular clean sources of energy, we avoid controversies surrounding some of the other alternative energy resources that revolve around the extent to which some of those resources are ‘clean’ and the costs involved in their utilization in large-scale
production. These debates typically do not concern wind energy, for there is somewhat of a consensus that wind energy is relatively clean and does not cause any negative externalities for the environment. There is also a relative comfort in the industry concerning large-scale wind farms and their economic viability.

We analyze the role of resource availability and institutions in wind power installment, beginning with a comparison of wind power adoption in Minnesota and Texas and then broadening our perspective to a global context by comparing Spain, Germany, and the United States. Throughout the analysis we provide succinct insight into the institutional structures that govern the market sector of electricity production in each of those cases and trace those differences back to the difference in the performance of the relevant economic sectors. In doing so we provide a rare illustration of the canonical work of Douglass C. North (1981, 1992) that is so heavily premised on the idea that the institutional structure of an economy determines the performance of that economy. To rephrase the premise bluntly: market forces are not the only and sometime not even the most important determinants of economic performance. The institutions that govern and regulate the markets have a huge impact not only on economic performance but also on long-term trends of technological innovation and economic growth. Neither technologies, nor prices are functions of supply and demand alone, they critically depend on the institutions that govern and regulate the complex activities of the market.

THEORETICAL FRAMEWORK

Neo-classical economic theory has one exogenous variable to explain variation and shifts in economic performance: technology (Mokyr, 1990). Technology is the only explanation as to why markets transition from one phase to another. Everything else is supply and demand and as long as technologies are constant and preferences remain stable across time, change should not be expected. But in the global economy of the 21st century where technology is internationally shared within days, what explains variations across countries in the implementation of such technologies in different markets?

Wind technology, the subject of this paper, is relatively simple and commonly known across different geographical and geo-political arenas. Why do some markets heavily invest in it while others do not? Of course, wind conditions vary across geographical regions, but holding such variations constant is a simple statistical exercise and doing so we still find considerable variation left. Moreover, we find that wind technology is more widely implemented in regions where conditions are less favorable for the implementation of the technology, such as in southwest Europe, than in regions where they are much more favorable, such as in the central United States. How does one explain this superficial contradiction?

In his breakthrough work that earned him the Nobel Prize in 1993, Douglass C. North (1990) provides an alternative explanation for variations in economic performance: institutions. In his seminal work, Professor North established that what he calls ‘the structure of the economy’ (North 1981, 1990) is just as potent an explanatory variable for the performance of the economy as technology and the usual market forces of supply and demand. While North’s work is well known and commonly hailed in academic circles, it has yet to show its potential in empirical applications. What North calls ‘the structure of the economy’ is a complex web of formal and informal institutions that are constantly in flux. With every legislation, to give just one example, the structure of the economy changes. The complexity and instability inherent in the institutional environment of any economy partially accounts for why the potent research program established by North has not been more successful in empirical applications. Unlike many empirical applications, our research is able to corroborate the institutional framework due to our focus on a limited, relatively simple part of the electricity-producing arena.
In what follows we show the straightforward connection of institutional arrangements that govern and regulate the production of electricity and the extent to which wind power is introduced as a major source of energy in those markets. We can assume that technology is constant across our cases, since the technology of harvesting energy through wind turbines is relatively well known and easy to implement. We control for weather conditions using widely available global maps of wind conditions across all regions of the globe. By analyzing only OECD countries we can further assume competitive markets and similar production costs for most input factors. Thus we can attribute much of the variance in the dependent variable, namely wind power capacity, to the variance in institutions. We go a step further and spell out the exact nature of the institutional structures to which we attribute the effect on the market.

METHODS

Our method of analysis has come to be known as ‘analytic narrative’ (Bates et al, 1998). Introduced in the mid 1990’s, the method is particularly fit for our task at hand. Formal models of mathematical economics are rigorous in kind and have a very high specificity of the elements that are used to construct them. As a result, they are such an extreme abstraction of reality that they can rarely be said to have any meaningful relevance to anything that occurs in real life market places. Analytic narrative, on the other hand, connects a more formal articulation of economic theory with the real world. You do not need much math or specificity to realize that a market equilibrium will occur where the demand and supply curves cross, or that if we increase or ‘induce’ demand this juncture will move rightward and, if the supply curve is not flat, upward as well. This is why ‘induced’ demand is generally theorized to cause an increase in the quantity a market will supply, often at higher prices. Technical terms can be employed to prove this, but the intuition behind this analytic exercise can serve as a ‘narrative’ upon which we can theorize without sinking into endless mathematical technicalities. From whence: ‘analytic narrative.’ ‘Analytic narrative’ does not imply ‘free style’ story telling. The analytic part has to come from clearly articulated propositions that are directly or indirectly derived from the rational choice theoretical perspective and the narrative must be enriched with solid empirical evidence to satisfy academic rigor and empirical testability.

Our analysis is simple: we observe variations across markets that cannot be explained by physical or technological factors. The global market allows us to assume that these markets face similar input production conditions. We restrict ourselves to OECD countries to allow us to assume similar consumption and demand conditions. Having held all of the above constant, we use the only exogenous variable left, the institutional variable, to provide a causal explanation for the variance. Throughout the analysis we supplement the exercise with careful quantitative empirical evidence to support our theoretical analysis in whatever shape way and form we can.

RESULTS AND DISCUSSION

TECHNOLOGY

One oft-repeated argument for the minimal deployment of renewable energies cites their non-competitive pricing with fossil fuels due to insufficient technology. Coal- and natural gas-fired power plants, the reasoning goes, produce electricity at a lower cost per kWh than renewables such as wind, and therefore prevail. However, recent studies show the contemporary economics to be more convoluted, for wind is currently cost-competitive in certain scenarios.

In 2010, the International Energy Agency ("IEA") compared the cost to produce baseload electricity from nuclear, coal, gas, and wind for projects commissioned by 2015 in North America,
Europe, and Asia Pacific. For the first time, the IEA found onshore wind power in some cases, depending on the local resources, to be cost competitive with coal, gas, and nuclear in all three regions, but especially in North America. Although the study assumes a reasonable yet highly uncertain USD 30 per ton CO₂ price, even without such a price the study concludes that wind would still be cost competitive. Two discount rates, or the interest rate at which money can be borrowed, were considered; the lower discount rate, 5%, favored capital-intensive low-carbon energy sources like nuclear and wind, while the higher, 10%, favored coal and natural gas.

A study conducted by the National Academy of Sciences ("NAS") in 2009, titled America's Energy Future, corroborates the IEA's findings within the United States. The NAS study determined onshore and offshore wind to be priced equally to other energy sources beginning generation in 2010 even in the absence of a price on carbon. Like the IEA's findings, however, the cost of wind-generated electricity varies widely based on available wind resources. Furthermore, both studies consider prices at the power-plant rather than system level, and so exclude transmission and grid expenditures. These are often higher for wind farms, but still only add approximately a few cents per kWh to the cost of electricity and most likely would not put wind at a significant disadvantage, the study concludes.

As final proof of the economic viability of wind-generated electricity, the Energy Information Administration ("EIA") arrived at the same conclusions as the previous two studies even when factoring transmission and grid expenses into the levelized costs. The study quantified the national average levelized costs for new electricity sources in 2016. To simulate a USD 15 per ton CO₂ emissions fee, the capital cost of coal and gas plants without carbon capture and sequestration ("CCS") were increased by 3%. Even without this price increase, though, conventional coal would only cost roughly 2 $/MWh less, which would not alter the study’s key findings. While the study found wind (149.3 $/MWh) on average to be more expensive than fossil fuel sources, such as conventional coal (100.4 $/MWh), regional wind costs ranged from 91 to 271 $/MWh. Thus, wind power in gusty areas outcompetes fossil fuel power even with transmission costs incorporated. Unfortunately, the study does assume a $15 per ton CO₂ emissions fee, the absence of which would decrease fossil fuel electricity costs further.

These three studies prove wind to be cost competitive with traditional energy sources (e.g. coal and natural gas) in certain regions. Technology therefore does not seem to be a significant limiting factor in the expansion of wind power capacity in regions that have sufficient wind resources.

RESOURCE AVAILABILITY AND INSTITUTIONS

Whereas renewable energy technology does not vary much across regions, renewable resources (i.e. wind) and institutions do differ greatly both between and among nations. As a result, any analysis of the impact of both variables on renewable energy adoption at a global scale would be highly complex and likely yield unintuitive and impractical conclusions. We instead first examined the effect of these two variables in a constrained case study of the wind power industry in the states of Minnesota and Texas, and then extrapolated our conclusions to a broader but still limited comparison of three nations, namely the United States, Spain, and Germany. In both investigations, we strove to answer three questions. First, which state or country would we predict to have the greatest wind power capacity based on the available resources? Second, does our prediction align with reality? And third, if not, why?

Case Study 1: Minnesota and Texas
**Installed Wind Power Capacity** To gauge the extent of wind power adoption in Minnesota and Texas, we employed two types of electricity data. The first, power capacity, represents the maximum possible production of electricity by wind turbines by ignoring capacity factors, resource (i.e. wind) availability, and losses from, for example, transmission and distribution. Table 1 summarizes the added and total wind power capacity in Minnesota ("MN") and Texas ("TX") over 2007, 2008, and 2009 as well as their national rank in cumulative capacity, per the American Wind Energy Association.

<table>
<thead>
<tr>
<th>Year</th>
<th>Added Capacity (MW)</th>
<th>Cumulative Capacity (MW)</th>
<th>National Ranking (Cumulative Capacity)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MN</td>
<td>TX</td>
<td>MN</td>
</tr>
<tr>
<td>2007</td>
<td>405</td>
<td>1618</td>
<td>1299</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4356</td>
</tr>
<tr>
<td>2008</td>
<td>455</td>
<td>2671</td>
<td>1754</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7118</td>
</tr>
<tr>
<td>2009</td>
<td>56</td>
<td>2292</td>
<td>1809</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9410</td>
</tr>
</tbody>
</table>

As shown above, Texas not only has significantly greater cumulative capacity than Minnesota as of 2009, but also has added significantly more capacity.

Another metric for measuring the size of a state's wind power sector is the actual amount of electricity generated. This amount incorporates that which capacity does not, such as transmission losses and capacity factors, and so can be easily compared to total generated electricity. The U.S. Department of Energy provides such a source of information for the electric power industry, as summarized in Table 2.

<table>
<thead>
<tr>
<th>Year</th>
<th>Wind (MWh)</th>
<th>Total (MWh)</th>
<th>Percent from Wind (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MN</td>
<td>TX</td>
<td>MN</td>
</tr>
<tr>
<td>2006</td>
<td>2,054,947</td>
<td>6,670,515</td>
<td>53,237,789</td>
</tr>
<tr>
<td></td>
<td>3.9</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>2,638,812</td>
<td>9,006,383</td>
<td>54,477,646</td>
</tr>
<tr>
<td></td>
<td>4.8</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>4,354,620</td>
<td>16,225,022</td>
<td>54,763,360</td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>4.0</td>
<td></td>
</tr>
</tbody>
</table>

Two conflicting comparisons between Minnesota and Texas can be drawn from the data presented in Table 2, depending on which variable one favors. By the raw quantity of wind-generated electricity, Texas’s wind sector once again dominates Minnesota’s, producing nearly quadruple the electricity in 2008. Conversely, Minnesota generates roughly twice as much of its electricity from wind than Texas, although this lead has been decaying. This seeming contradiction is due at least partially to substantially lower total electricity generation in Minnesota, which is roughly 13% of that in Texas. Thus, one can reasonably conclude that Texas has more effectively adopted wind power than Minnesota.

**Resource Availability** The annual average wind speeds at 80 m elevation for Minnesota and Texas, maps of which have been created by the U.S. Department of Energy, serve as an indicator for the states’ overall wind resources. Wind speed directly determines the potential for wind power in an area; winds must have annual average speeds greater than about 6.5 m/s to be suitable for wind power development ("Wind Powering America” 2010). Another crucial determinant of wind power viability, however, is the area’s location relative to cities, for wind turbines in isolated regions require large investments in new transmission lines, a prominent barrier to wind power expansion across the United States (Wiser and Barbose 2008). Therefore, both wind speed and distance from urban centers must be considered in judging the strength of wind resources for a given area.
Although Texas has some of the strongest winds in the United States, its winds of more moderate speeds are much closer to urban centers. The state’s breeziest region is the Panhandle, the majority of which has winds that average approximately 8.5 m/s in speed. Unfortunately, its largest cities, namely Houston, San Antonio, and Dallas, reside far to the southeast of the Panhandle, at distances of about 450, 350, and 240 miles, respectively. Even so, while not as windy as the Panhandle, most of the northwestern and central Texas interior is also suitable for wind power development, containing winds measured mostly between 6.5 and 8 m/s in a patchy distribution. Both Dallas and Austin sit roughly 25 miles from such windy landscapes, although Houston, the largest city, still lies approximately 150 miles away.

Minnesota’s wind resource situation mirrors that of Texas. Its strongest winds, which average speeds similar to those in the Texas Panhandle, occur in its southwestern corner, about 100 miles from Minneapolis and Saint Paul, known collectively as the Twin Cities, and 115 miles from Rochester, the third largest city in the state after the Twin Cities. However, these cities do not neighbor lands with significant wind resources. The Twin Cities are separated from winds averaging 7.0 to 7.5 m/s by a slim 40 miles, whereas Rochester is only about 10 miles from winds of speeds between 7.5 and 8.0 m/s.

Ultimately, Minnesota and Texas have similar wind resources with respect to both intensity and relative location. For the disparity in wind power capacity between the states to be explained by available resources alone, Texas would be expected to have either faster or better situated winds than Minnesota. Given that this is not the case, wind resources do not explain Texas’s greater wind power capacity.

**Institutions** To better understand how each state's institutions have affected its wind power sector, we examined some of the divergent institutions, particularly those that are political or regulatory, that pertain directly to wind power. We found that Minnesota and Texas have similar but distinct incentives, rules, policies, and regulatory agencies, the result of which has been Texas being better able to expand its transmission grid and increase its wind power capacity.

In 2007, Minnesota enacted legislation implementing a state-wide Renewables Portfolio Standards (Minn. Stat. § 216B.1691). The legislation mandated Xcel Energy, the largest utility in Minnesota, generate 30% of its electricity from renewables by 2020, and all other utilities generate 25% of their electricity from renewables by 2025. Furthermore, 25% of Xcel's electricity derived from renewables had to be from wind or solar, with a maximum of 1% from solar. Thus, a high mandate was set for wind energy, although with respect to the construction of additional transmission lines, §216B.1691 (Subd. 2) only required utilities to “make a good faith effort.”

Passage of the RPS immediately spurred a nearly five-fold increase in the capacity of proposed wind projects to the Midwest Independent Transmission Operator ("MISO"), the regional transmission operator ("RTO") responsible for managing the transmission grid in Minnesota along with twelve other states and Manitoba. If realized, these proposals would have exceeded the ultimate mandated amount of wind power generation by 340% (Marcus 2010). Unfortunately, none of these proposals have begun operations due to the formation of an extremely lengthy backlog of projects awaiting MISO’s approval (Marcus 2010, Office of Energy Security 2010). As of August 27, 2010, the most recent wind turbine project to leave the MISO queue with completed reports first joined the queue on April 25, 2006 (Midwest ISO 2010). This extraordinary lethargy in the approval process is reflected in the wind capacity statistics for Minnesota (see Table 1), particularly in capacity additions in 2009. Indeed, in 2008 the Federal Energy Regulatory Commission approved a plan submitted by MISO to reform its queue by, among other changes, moving from a first-come first-serve basis to prioritizing projects based on their likelihood of approval as well as adding a “fast track” option (FERC 2008). Unfortunately, this reform has yet to bear fruit.
Besides from the RPS and a sluggish approval process for projects, wind power capacity in Minnesota also depends on the transmission grid. As previously mentioned, the state's highest wind potential exists along the western and southwestern borders of the state, far from the Twin Cities and Rochester. New wind projects in these areas would therefore require, in order to be effective, extensive construction of transmission lines to transport the generated electricity. To this end, eleven transmission-owning utilities, including Xcel Energy, have formed a joint initiative named CapX2020, which has proposed five large grid expansion projects to the Minnesota Public Utility Commission. However, only one of these projects is expected to be in service in 2011, with the other four forecasted to be completed between 2013 and 2015 (CapX2020 2010). This institutionally-derived barrier only further obstructs additional wind energy deployment in the state.

Further hindering the expansion of the transmission grid has been a collective action failure among the grid stakeholders, a phenomenon documented by Alfred Marcus (2010). In 2007, an eclectic coalition consisting of environmental groups, citizens, utilities, and regulators formed to advocate for the passage of the RPS. Although successful in this endeavor, the coalition weakened during implementation of the RPS as conflicting views over unforeseen issues created tension among the members. The construction of new transmission lines, in particular, spread discord among the stakeholders; environmental groups and citizens opposed new lines for fear of their deleterious effects on wildlife and property, respectively, while the utilities and regulators, knowing their crucial role, strongly advocated for new lines. To add even further to the confusion, various stakeholders randomly entered and exited the debate, making collective action even more difficult. For instance, the U.S. Department of Energy in 2008 released a report that included their own plan for transmission grid expansion in Minnesota (20% Wind Energy by 2030 2008), further obscuring the facts and stakes of the issue (Marcus 2010).

Texas first passed its Renewable Portfolio Standards in 1999, but amended it in 2005 to update the mandated minimum renewable energy capacity to 10,000 MW by 2025 (Tex. Stat. §25.173), or roughly 5% of the state’s total electricity production (see Table 1). Remarkably, Texas achieved the mandated levels of electricity generation in early 2010 (ERCOT 2010), thanks to its rapid expansion of wind power capacity (see Table 1). In addition to the electricity generation requirement, the 2005 amendment to the RPS, passed as Senate Bill 20, grants the Public Utility Commission of Texas ("TPUC") the authority to order an electric utility or distribution and transmission utility to expand or construct new transmission facilities (2005: Sec. 1). This authority gives the TPUC considerable power to ensure grid expansion occurs in a timely and efficient manner. Indeed, another part of S.B. 20 ordered the TPUC to, after consultation with related entities such as ERCOT, designate areas with exceptional wind resources and available lands as Competitive Renewable Energy Zones ("CREZs"). Once selected, TPUC would then commission utilities to expand the transmission grid to these CREZs, thereby ensuring adequate transmission capacity regardless of the status of wind projects in the region. In 2008, TPUC created five CREZs, two in the Panhandle and three in West Texas, and has already assigned billions of dollars to transmission projects (CREZ Transmission Program Information Center 2010).

In addition to rapidly installing new transmission lines, Texas has also continuously brought online new wind projects. This is at least partially due to the fact that Texas's dominant RTO, the Electric Reliability Council of Texas ("ERCOT"), operates only in Texas, covering around 75% of the state including its major urban centers. Because of its intrastate nature, ERCOT is only subject to state authority and rules and so avoids a host of federal regulations (Fleisher 2008), allowing it to operate more freely. Furthermore, since ERCOT's jurisdiction coincides with that of the TPUC, the two entities can collaborate
more efficiently than other states whose RTOs cover multiple states. The result: steady and rapid expansion of wind power capacity in Texas, as evidenced by the state's booming wind power capacity (see Table 1).

While the political and regulatory institutions of Minnesota and Texas overlap in many respects, key differences exist among them, particularly with respect to the states' RPSs and regulatory processes. Due to these differences, Texas has more power to expand its transmission grid, which it has used to its advantage. Wind projects in Texas are also not obstructed, be it by backlogs or insufficient transmission lines, as they are in Minnesota. Ultimately, it has been these institutional differences, rather than technology or resource availability, that have produced the divergence in wind power capacity between Texas and Minnesota.

**Case Study 2: United States, Spain and Germany**

**Installed Renewables Capacity** The percent of total electricity generated by renewable sources in Germany, Spain, and the United States for the year 2009 differs markedly. Germany (16.1%) and Spain (29.1%) have both far exceeded the United States (10.5%) in their adoption of renewable energies (defined as wind, geothermal, solar, biomass, and hydro) as a percent of total electricity generation. In regards to wind power alone, in 2009 the United States, Germany, and Spain generated 1.8%, 6.5%, and 13.8% of their total electricity from wind, respectively. A preliminary investigation into the cause of these disparities in wind-derived electricity reveals that they are driven not by available resources, but rather national institutions.

**Resource Availability** To better understand the root of the gap in wind-derived electricity between the United States and its European counterparts, Spain and Germany, we first examined the available wind resources in each nation. Archer and Jacobson, in a 2005 study, mapped annual average wind speeds at 80 m elevation within the three nations. The maps indicate that the United States, of the three nations, has the greatest wind intensity, particularly in the Midwest, where winds mostly attain speeds of between 6.9 and 8.6 m/s, and along its coasts, which have areas with greater than 9.4 m/s wind speeds. Germany, on the other hand, has fairly moderate wind resources, which are concentrated mostly in its northern half and mostly below 9.4 m/s in speed. Spain, finally, appears to have very limited amounts of wind above 5.9 m/s. With respect to the location of these high-intensity winds, however, the United States does not have a clear advantage, for the wind-rich Midwest is far removed from the densely populated coasts. Many of Germany’s most populated cities, on the other hand, including Berlin, Hamburg, and Bremen, sit in the northern part of the nation, close to the nation’s best winds. Valuing the location of Spain’s high-intensity winds, unlike the other two nations, does not seem to be possible on a broad basis, due to their apparently diffuse nature. Regardless, the wind maps suggest that the available wind resources within each nation do not explain the high levels of wind power in Spain and Germany relative to that in the United States.

**Institutions** The institutions, political and otherwise, of Spain, Germany, and the United States that affect renewable energies are incredibly diverse, with substantial similarities and differences existing among them. Table 3 lists the various policies that each nation has enacted.

<table>
<thead>
<tr>
<th></th>
<th>Feed-in tariff</th>
<th>RPS</th>
<th>Capital subsidies, grants, or rebates</th>
<th>Investment or tax credits</th>
<th>Public investment, loans, or financing</th>
<th>Energy production payments or tax credits</th>
<th>Sales tax, energy tax, excise tax, or VAT reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Spain</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>U.S.A.</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
Perhaps the single greatest policy difference between the United States and Spain and Germany is that the latter two nations have each adopted a feed-in tariff, passed and revised most recently in 1997 and 2004 and 1991 and 2009, respectively (Spain: Renewable Energy Plan; Germany: Renewable Energy Sources Act). Feed-in tariffs essentially guarantee fixed payments, per unit of energy, for electricity generated by renewable energies, consequently negating the uncertainty of what price, if any, utilities would pay for renewably-generated electricity (Sawin 2004). The efficacy of feed-in tariffs relative to other policies aimed at promoting renewable energies has been well established (Mitchell et al. 2006, Butler and Neuhoff 2004), although some question its long-term impact (e.g. Sijm 2002). While the feed-in tariffs of Spain and Germany differ in some respects (see Ragwitz and Huber 2005), they both, in addition to ensuring minimum payments for renewably-generated electricity, guarantee grid access to renewable projects, a promise enforceable by state orders to transmission operators (Ragwitz and Huber 2005). The United States has no such national mechanism in place, and so has no such power to force the expansion of its transmission grid. This same scenario emerged in the case study of Minnesota and Texas, where the state that had the authority to force utilities to expand the grid for renewable projects – Texas – also had higher renewable power capacity.

Apart from a feed-in tariff, Spain and Germany also have a national RPS, which the United States does not. Germany’s RPS, established in the aforementioned Renewable Energy Sources Act, mandates 30% of all consumed energy to be produced by renewable sources by 2020. Spain’s RPS, codified in its Renewable Energy Plan, is slightly less ambitious, aiming for 20% of its energy consumption to be from renewable sources by 2020. While the specifics of RPSs vary in accordance with their context, they all, at a minimum, guarantee a market share for renewable energy, thereby signaling a strong commitment to the market and typically spurring investment (Jaccard 2004). Recent studies of U.S. states have suggested that RPSs do, in fact, lead directly to increased renewable energy capacity (Wiser and Barbose 2008, Rabe 2007). However, as we saw in the case of Minnesota and Texas, RPSs alone are not sufficient to guarantee continual growth in renewable energy capacity.

The extensive legacy of the German and Spain feed-in tariff and RPS policies hints at an even deeper disparity between the United States and Germany and Spain: the extent of institutional uncertainty. Businesses, including those in renewable energies, have been shown to react negatively to perceived institutional uncertainty by shifting investment to more stable jurisdictions (e.g. Luthi and Wustenhagen 2010), a notion reflected in the renewable energy capacities of the three studied nations. On the one hand, Germany and Spain have had meaningful policies, including an RPS and feed-in tariff, aimed at increasing renewable energy capacity since 1997 and 1991, respectively. Such long-term commitments have indicated a strong support for renewable energy and decreased institutional uncertainty, which is reflected in high renewable power capacity. The United States, on the other hand, does not have, nor has ever had, an RPS or feed-in tariff. Furthermore, while it does have a panoply of financial incentives aimed at renewable energies (as do Germany and Spain), their existence has historically been highly uncertain. For instance, one of the U.S.A.’s major financial incentives, the Production Tax Credit (PTC), has expired three times in the past 15 years, in 1999, 2001, and 2003. Each year following its expiration, renewable energy power capacity growth all but ceased, dropping to less than 20% of growth in the previous year (Combs 2010). Such vacillation in policy-making is but one of many examples that have plagued the United States renewable power industry, hence the nation’s low wind power capacity.
CONCLUSION & FUTURE PLANS

We study of the discrepancies in the growth of alternative energy production industries across U.S. states and OECD countries applying basic derivatives of neo-classical economics to argue that in a global economy where renewable energy technologies are common knowledge, faltering evolution of major production facilities in some countries, particularly the U.S.A., is somewhat of a puzzle. Given the competitive cost of production and the relative environmental and, hence, political advantage of renewable energies, renewable energy resources should be used more widely in the market of energy production and in particular in the market of electricity production where many technological challenges have been met by now. Ruling out technology and price as potential explanations, we restrict our analysis to OECD countries to control for preferences and trends of consumption as well. After ruling out those variables, we find that the institutional structure variable promoted by Nobel Laureate Douglass C. North (1981, 1990) as an exogenous variable helps us sort out our empirical puzzle.

Using analytic narrative as a method we ‘tell the story’ of five states and countries, namely Minnesota, Texas, the U.S.A., Germany and Spain, to examine our central hypothesis that different institutions will promote to a greater or lesser degree the growth of the wind power industry. Our main analytical argument comes from a commonly ascertained proposition in the neo-classical economic literature according to which high transaction costs and high uncertainty will delay economic growth whereas lower transaction costs and uncertainty will enhance economic growth. We go into great length to analyze the institutional structures of our five cases to be sure to specify the exact way in which the institutional structure affects the economic performance in the domain under study. We supplement our analysis with almost all available data on the subject and add structural validity by relying on other studies that point in the same direction.

We find that ‘institutions matter.’ Our case studies clearly indicate that institutional control of the grid and its expansion, coupled with some key policies such as feed-in tariffs, explain most of the variance in the degree of expansion of the industry. While for methodological reasons we have limited ourselves to wind energy policy in OECD countries, we have every reason to believe and some anecdotal evidence to suggest that our findings generalize beyond just wind based energy and way beyond the OECD.

Besides the academic value of our research, it clearly implies some very straightforward policy recommendations: expanding the grids to accommodate energy produced by renewable energy sources, and adopting long-term government-backed assurances that address the significant initial investments of beginning renewable energy production. Such action can go a very long way in changing the nature of the industry and allowing cleaner and cheaper inputs of production like solar and wind to play a more significant role in this sector.

Some caveats. First, we want to be abundantly clear that the assurances and controls our analysis suggests may be significantly instrumental for the spread of alternative and cleaner energy production do not require much government intervention at all. They do require, however, our government to express a long-term commitment to send a clear message of confidence to investors. Second, in calculating the costs and benefits involved with renewable energies, we only accounted for the supply side. There is every reason to believe that the spread of alternative energy production will do much more good than what our analysis suggests by, for instance, improving our environment, creating new jobs and reducing the price of electricity to consumers if for nothing else, revitalizing the competitive forces in this industry.

Future Plans: We are currently pursuing three development tracks of our project. CNISS has teamed with the School of Engineering to create a unique interdisciplinary course to cover all aspect of DEPS, technology market and institutions as well as physical geographical constraints. CNISS is working with
its collaborator institutions to create the most expansive database on the subject ever put together. We are pursuing several grant opportunities with the NSF and private foundations.

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Study on Stress and Bioremediation Mechanisms of Microorganisms Exposed to Metal Oxide Nanoparticles

Yinjie Tang, Pratim Biswas, Bing Wu
Department of Energy, Environmental and Chemical Engineering, Washington University, St. Louis, USA

Achariya Suriyawong
Department of Environmental Engineering, Chulalongkorn University, Bangkok, Thailand

Abstract
The eco-toxicity of six types of transition metal oxide nanoparticles (NPs) (TiO$_2$, NiO, ZnO, CuO, Co$_3$O$_4$ and Fe$_2$O$_3$) was studied extensively in both aqueous culture medium and aerosol exposure (spraying these particles directly on cell surface). In the aqueous medium, only NiO NPs showed strong inhibition (>30%) to cell growth when concentration was over 2mg/L. In contrast to aqueous exposure where the particles and bacteria had limited interactions, aerosol exposure of three metal oxide NPs to E.coli enhanced NPs’ toxicity to cells and dramatically reduced cellular viability: electrospraying of NiO, CuO and ZnO NPs (20nm, 20μg) reduced the total number of living E.coli compared to the control experiments by more than 88%, 77% and 71% respectively. Spraying larger ZnO NPs (480nm, 20μg) caused much less lethality to E.coli cells, which indicated the size effect to the NPs’ toxicity. On the other hand, electrospraying of other two types of metal oxide NPs (TiO$_2$ and Co$_3$O$_4$) decreased the lethality to cells (to below 20%). The reason was due to their extremely low solubility in aqueous medium. Fe$_2$O$_3$ NPs showed no antibacterial activities under both aqueous exposure mode and aerosol exposure mode. Furthermore, we extended eco-toxicity study to different bacterial species using ZnO NPs. Five types of microorganisms have been investigated: pathogenic bacteria (non-virulent species Mycobacterium smegmatis), metal reducing bacteria (Shewanella oneidensis MR-1), blue-green algae (Cyanotohece 51142), yeast (Saccharomyces Cerevisiae), and enterobacterium (Escherichia coli). Shewanella oneidensis MR-1 and Escherichia coli could tolerate the ZnO NPs’ stress in the aquatic mode, while M. smegmatis and Cyanotohece 51142 could be inhibited seriously in a dose response manner in the aquatic mode. Further studies showed that the antimicrobial activities of aerosolized metal oxide NPs were mainly determined by three key factors: 1) the solubility of particles; 2) the toxicity of the metal ions; 3) the mode of exposure. The above observations provided the guidelines for potential application of electrosprayed NPs to disinfect airborne pathogens. Finally, we also discovered some novel applications for biotechnology using metal NPs: 1) plasmonic nanoparticles can be used to tune light wavelength for improving algal photosynthesis; 2) nanoparticle can also be used for delivery of genes into microbes; 3) nanoparticle can protect metal reducing bacteria under UV stresses.

I. Introduction and Background
Transition metal oxide nanoparticles (NPs) have widely been applied as industrial materials (e.g. semiconductors, photocatalysts, etc.) as well as for medical research and energy generation. Commercial applications of metal oxide NPs have received great attention due to the novel characteristics of nanoparticles: nano-scaled size; hugely active surface area; efficiently chemical reactivity; uniquely physical adsorption ability and mobility. This is attributable to the fact that when the physical dimensions of a material decrease to the nanoscale, its mechanical, electrical, thermodynamic, and other types of properties are significantly varied [1-3]. Nano-metal oxides have been widely applied in our daily life. However, their ecological effect is still not clear [4]. Some metal NPs can strongly interact with microorganisms and cause the physical damage. Other environmentally relevant bacteria exhibit a capability in reducing metallic ions to lower valence species or the metallic state. For example, Shewanella spp. and Geobacter spp. could transform Fe(III) to Fe(II) at the surface of an iron oxide
nanoparticle and *Desulfovibrio* spp. could reduce Pd(II) on the surface of Pd nanoparticles [5-8]. Therefore, the main goals of this project are to address the environmental effects of nano-sized metal oxide particles. The detailed research objectives include:

1. To study the responses of different microbial species to different metal oxide NPs.
2. To compare the NP antibacterial properties under aqueous and aerosol exposure modes.
3. To examine the light-dependent microbial response of Cu-doped TiO₂ NPs.
4. To explore the bioremediation capability of environmentally relevant bacteria after NP stress.

2. Research Methods

**Synthesis of copper doped TiO₂ NPs.** A flame aerosol reactor (FLAR) with a three-port co-flow diffusion burner was used to synthesize Cu-doped TiO₂ NPs (~ 35 nm) [9]. NiO, ZnO, Fe₂O₃, Co₃O₄, CuO, and TiO₂ NPs (~ 20-30 nm) were purchased from NanoAmor (Houston, USA).

**Cultivation of the organisms with NPs.** Five microbial species were used: *M. smegmatis* was grown in a Sauton liquid medium at 37°C; *S. oneidensis* MR-1 was grown in a MR-1 medium at 30°C; *E. coli* were grown in a M9 medium at 37°C; *Cyanothecae* 51142 was grown in an ASP2 medium at 30°C under continuous light (50 µmol photons m⁻² s⁻¹); and *S. cerevisiae* was grown in a yeast synthetic-defined (SD) medium at 30°C. All cultures (50 mL) were grown in flasks shaken at 150 rpm.

**Growth of cells with NPs in aqueous mode** The bacterial cells (5 mL, initial OD₆₀₀ ~0.05) were mixed with NPs at a certain of concentration. The cells’ growth was monitored by measuring their optical density at 600 nm (OD₆₀₀), using a UV spectrometer (Thermo Scientific, USA).

**Cell survival after electrospray NPs.** An aliquot of *E. coli* (0.2 mL, total cell number ~8×10⁸) was first filtered onto a polyvinylidene fluoride (PVDF) membrane (0.22 µm pore size, 1.25×1.25 cm², Millipore, USA) to form a loosely-attached cell layer. The membrane was placed in the center of the deposition stage of electrospray system, and NPs were electrosprayed on the loosely-attached cell layer for 10 min. After spraying, the membrane was put into a tube with 5 mL of M9 minimal medium, and the cells were washed from the membrane by a vigorous vortex. To measure the total number of living cells in this aqueous medium, a 0.1 mL sample was diluted in a series before being spread onto LB agar plates. The colony forming units (CFU) were counted after the plates were incubated at 37°C for ~24 h.

**Observation of NP and cell morphologies.** TEM was used to image the aggregation of NPs. The samples were inspected in the TEM (H7500, Hitachi, Japan) at 80 kV using the HR mode, and photographed by a digital camera (FEI, USA). SEM was employed to observe cell morphologies. The sample were deposited on a piece of membrane and were fixed by adding 2% glutaraldehyde. After 2 hours, the samples were washed in 0.10 M sodium cacodylate buffer for 20 minutes three times. Then the samples were dehydrated in series of 10 minute washes in 50%, 70%, 85%, 95% and 100% ethanol and further were dried with freeze-drier equipment (Labconco, USA). The samples were gold-coated using a sputter gun (SPI supplies, USA). Photographs of the sample structure were observed and taken with a SEM (FEI, USA). Meanwhile, the interactions of NPs and cells were also observed under a light microscope (Zeiss, USA), and the images were taken by a built-in camera (Nikon, Japan).

**Measurement of soluble ionic copper.** Cu-doped TiO₂ NPs or NPs with cells were removed from the culture by high speed centrifugation (19,000 ×g) for 20 minutes, after which the supernatant was collected and filtered (0.22 µm, Nylon, Millipore, USA). The ionic copper (Cu²⁺) concentrations in the supernatant were determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS, Agilent, USA).
3. Results and Discussion

Response of different microbial species to ZnO NPs [10, 11]

Table 1 displays the different growth responses of microorganisms to ZnO NPs (20 nm) in the aquatic medium. ZnO NPs apparently inhibited the growth of *M. smegmatis* and *Cyanothece 51142* in a dose response manner. However, ZnO NPs (up to 40 mg/L) or 16 mg/L Zn$^{2+}$ did not suppress the growth of *S. oneidensis*, *S. cerevisiae* or *E. coli*. Normally, *Daphnia* species has been used to assess Zn$^{2+}$ toxicity (based on the mortality of *Daphnia* species after one week of exposure), but our study shows that zinc toxicity could be more quickly assessed by *M. smegmatis* in 1-2 days.

Table 1. Inhibition to microbial biomass production (initial OD$_{600}$=0.1) and GFP production of *E. coli* in the presence of ZnO NPs.

<table>
<thead>
<tr>
<th>Species</th>
<th>*Inhibition rates (%) in presence of ZnO NPs or Zn$^{2+}$</th>
<th>Inhibition of growth in presence of ZnO NPs (20 mg/L) after adding EDTA</th>
<th>Inhibition of GFP production (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inhibition rates (%)</td>
<td>NPs (mg/L)</td>
<td>Zn$^{2+}$ (mg/L)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td><em>S. oneidensis</em></td>
<td>9±8</td>
<td>11±6</td>
<td>3±13</td>
</tr>
<tr>
<td><em>M. smegmatis</em></td>
<td>18±11</td>
<td>38±8</td>
<td>60±19</td>
</tr>
<tr>
<td><em>Cyanothece 51142</em></td>
<td>7±16</td>
<td>69±16</td>
<td>74±19</td>
</tr>
<tr>
<td><em>S. cerevisiae</em></td>
<td>-3±3</td>
<td>-2±6</td>
<td>-1±2</td>
</tr>
<tr>
<td><em>E. coli</em></td>
<td>1±5</td>
<td>6±10</td>
<td>3±6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

* Inhibition rates were calculated based on the cell densities obtained from different culture conditions. The OD was measured after culturing all microbial species to the late exponential growth phase:

\[
\text{rates} (\%) = \left\{1 - \frac{OD(\text{stress condition})}{OD(\text{control condition})}\right\} \times 100\%
\]

Effect of metal oxide NPs on *E. coli* growth under aqueous exposure [10]

It is well known that the ions of some transition metals display toxic effects on biological systems. Table 2 indicates that the most of the ionic species tested in this study inhibited *E. coli* growth when ion concentrations were above 20 mg/L: Ni$^{2+}$, Co$^{2+}$, Zn$^{2+}$, and Cu$^{2+}$ showed strong inhibition of microbial growth, while Fe$^{3+}$ had relatively low toxicity. However, all of the tested metal oxide NPs except NiO showed no significant growth inhibition of *E. coli* at a concentration of 20 mg/L. NiO NPs showed inhibitory effects on cell growth at concentrations of 20 mg/L and 100 mg/L (30% and 46% respectively), but a negligible effect at a low concentration of 2 mg/L. Co$_3$O$_4$ and Fe$_2$O$_3$ NPs displayed extremely low solubility (less than 0.1 mg/L). Therefore, Co$_3$O$_4$ and Fe$_2$O$_3$ NPs could not inhibit *E. coli* growth. NiO, ZnO and CuO NPs (20 mg/L) released 0.5, 1.5 and 2.7 mg/L of metal ions in the aqueous system after 8 h. At this concentration level (i.e., ~2 mg/L), these metal ions showed relatively low growth inhibition (8–30%). The antimicrobial activity of metal oxide NPs was associated with their solubility and the ionic toxicity. NiO NPs (20 mg/L) in the aqueous medium had apparently higher inhibition (~30%) of cell growth than its released Ni$^{2+}$ ion (~0.5 mg/L).
Table 2. Growth inhibition rate (%) of *E. coli* in the presence of NPs and metal ions in the aqueous medium.

<table>
<thead>
<tr>
<th>Metal Ions (mg/L)</th>
<th>NiO (Ni²⁺)</th>
<th>ZnO (Zn²⁺)</th>
<th>Fe₂O₃ (Fe³⁺)</th>
<th>Co₃O₄ (Co²⁺)</th>
<th>CuO (Cu²⁺)</th>
<th>TiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>7±12</td>
<td>7±9</td>
<td>-22±5</td>
<td>1±4</td>
<td>13±6</td>
<td>NA</td>
</tr>
<tr>
<td>20</td>
<td>43±9</td>
<td>12±8</td>
<td>-15±19</td>
<td>49±9</td>
<td>67±12</td>
<td>NA</td>
</tr>
<tr>
<td>100</td>
<td>85±4</td>
<td>38±9</td>
<td>-11±6</td>
<td>80±7</td>
<td>78±5</td>
<td>NA</td>
</tr>
<tr>
<td>NPs (mg/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>14±5</td>
<td>1±9</td>
<td>5±9</td>
<td>-8±21</td>
<td>2±7</td>
<td>0±5</td>
</tr>
<tr>
<td>20</td>
<td>30±7</td>
<td>21±15</td>
<td>-16±24</td>
<td>-11±12</td>
<td>8±12</td>
<td>-6±23</td>
</tr>
<tr>
<td>100</td>
<td>46±10</td>
<td>9±22</td>
<td>-11±25</td>
<td>0±15</td>
<td>27±13</td>
<td>8±9</td>
</tr>
</tbody>
</table>

NA: not applicable

\[
\text{Inhibition Rate(%) = } \left[1 - \frac{OD(8h, \text{with NPs}) - OD(2h, \text{with NPs})}{OD(8h, \text{without NPs}) - OD(2h, \text{without NPs})}\right] \times 100% \]

Effect of aerosolized metal oxide NPs on *E. coli* survival [10]

Metal oxide NPs appeared to aggregate in the aqueous system. Although the original sizes of all of the commercial purchased NPs were 20~30 nm, their actual sizes in the aqueous mediums were much larger (from ~270 nm to ~1056 nm). The aggregation of NPs can reduce their nano-size associated effects on cellular function. On the other hand, environmental stresses could also trigger bacteria to form flocs and thus avoid direct exposure to NPs. These aggregation phenomena might strongly limit the interactions between particles and bacteria. To improve the ability of NPs to have direct contact with bacteria, this study employed an electrospray technique to disperse NPs directly onto the bacterial surface (a thin layer of cells on the PVDF membrane). In the aerosolized NPs solution, the aggregations of NPs can be significantly reduced (though not completely avoided) by at least one order of magnitude. Such an exposure mode could enhance the nano-size associated effects on cellular functions. Table 3 shows the percentages of reduced bacterial viability after cells were exposed to aerosolized NPs. These percentage values were based on the total living cell numbers according to the CFU count. Compared to the control (electrospraying the buffer solution only), NiO, CuO, and ZnO NPs significantly reduced viability of *E. coli* even with a short exposure time (i.e., 10 min). The sprayed NP amount was 4 μg in total, equivalent to the NP amount in a 0.2 mL aqueous medium at a NP concentration of 20 mg/L. Viable cells were reduced by 45% for NiO NPs, 52% for ZnO NPs, and 35% for CuO NPs. Increasing the sprayed NP dose up to 20 μg (equivalent to the NP amount in a 0.2 mL aqueous medium at a NP concentration of 100 mg/L) could further enhance NP lethality to bacteria. Viable cells were reduced by 88% for NiO NPs, 71% for ZnO NPs, and 77% for CuO NPs. However, less soluble Co₃O₄ NPs and non-soluble TiO₂ NPs displayed low toxic effects on *E. coli* after electrospray (viabilities were reduced less than 20%). Fe₂O₃ NPs showed no antimicrobial activity under the both exposure modes.

Table 3. Reduced percentage (%) of *E. coli* viability after exposure to aerosolized metal oxide NPs.

<table>
<thead>
<tr>
<th>Spray amount*</th>
<th>NiO</th>
<th>ZnO</th>
<th>Fe₂O₃</th>
<th>Co₃O₄</th>
<th>CuO</th>
<th>TiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 μg</td>
<td>45±16</td>
<td>52±16</td>
<td>-21±23</td>
<td>12±22</td>
<td>35±4</td>
<td>19±24</td>
</tr>
<tr>
<td>20 μg</td>
<td>88±5</td>
<td>71±19</td>
<td>-12±14</td>
<td>5±14</td>
<td>77±11</td>
<td>21±19</td>
</tr>
</tbody>
</table>
Light-dependent microbial response to Cu-doped TiO$_2$ NPs

Compared to control experiments without NPs, TiO$_2$ NPs did not significantly reduce $M$. smegmatis' viability under complete dark or fluorescent light (Figure 1A). However, TiO$_2$ NPs caused significant more lethality (~90%) to cell under UV light. Meanwhile, if TiO$_2$ NPs were doped with copper, their antimicrobial activities were strongly enhanced. Under dark or fluorescent light, the lethality of NPs increased with the content of doped Cu in NPs, where $M$. smegmatis was completely unviable if the Cu doping amount is over 3.0%. Under dark or fluorescent light conditions, neither TiO$_2$ NPs nor Cu-doped TiO$_2$ NPs can reduce viability of $S$. Oneidensis MR-1 (Figure 1B) and $E$. coli (Figure 1C). The outer membrane of both species (Gram-negative bacteria) contains lipopolysaccharides, and they have an ability to produce extracellular polymeric substances (EPS) under unfavorable conditions, both of which provide resistance against NP stress [11]. Furthermore, this phenomenon was also related with the fact that $S$. oneidensis MR-1 species may have evolved a capability to reduce toxic metal ions [12] and both species could tolerate such a level of oxidative stresses from hydroxyl radicals.

$S$. oneidensis MR-1 and $E$. coli were highly sensitive to UV light (Figures 1B and 1C) as previously reported [13, 14]. However, the presence of Cu-doped TiO$_2$ NPs tended to dramatically increase the viability of $S$. oneidensis MR-1 and $E$. coli. Interestingly, for $S$. oneidensis MR-1, the viable cell amount was associated with a doping amount of copper on TiO$_2$ NPs. Compared to control (cells without NPs), 1% Cu-doped TiO$_2$ NPs showed highest improvement of cell survival by 196-fold. Accordingly, SEM images (Figures 2) revealed that the surface structure of stressed cells became twisted and rough after UV exposure (clear morphological changes).

![Graphs showing responses of microorganisms to NPs](https://example.com/graphs.png)

**Figure 1.** Responses of microorganisms to NPs (~35 nm, 20 mg/L, 100% anatase crystalline structure) under different conditions. (A) $M$. smegmatis; (B) $S$. oneidensis MR-1; (C) $E$. coli. In dark (White column with solid line); Under fluorescent light (Grey column with solid line); Under UV light (White column with dot line). (1) Cells without NPs; (2) Cells with TiO$_2$ NPs; (3) Cells with 0.25% Cu-doped TiO$_2$ NPs; (4) Cells with 0.5% Cu-doped TiO$_2$ NPs; (5) Cells with 1.0% Cu-doped TiO$_2$ NPs; (6) Cells with 3% Cu-doped TiO$_2$ NPs; (7) Cells with 5% Cu-doped TiO$_2$ NPs; (8) Cells with 7% Cu-doped TiO$_2$ NPs; (9) Cells with CuO NPs.
Both TiO\textsubscript{2} and Cu-doped TiO\textsubscript{2} NPs (~35 nm) tended to aggregate in the aqueous environments, and the formed bulk NP had a mean particle size of ~700 to 900 nm. On the other hand, \textit{S. oneidensis} MR-1 or \textit{E. coli} produced a large amount of extracellular polymeric substances (EPS) under stress, which led to cell aggregations or easily facilitated cells to attach on solid surfaces. Both properties promoted the interaction of NPs and cells, which led to form the flocs ranging from a few microns to half hundred microns under non-agitation conditions. Therefore, the formed flocs may be considered as a protective strategy, which sheltered the immobilized cells within the complex from UV induced damage. To further explain that the formed cell-NP floc to be a main reason for protecting cells from UV, we observed the responses of \textit{S. oneidensis} MR-1 to HA-coated 1% Cu-doped TiO\textsubscript{2} or polystyrene NPs. Natural organic matter (NOM) plays a key role in the biogeochemical process of nature water [15]. The presence of NOM in the aqueous environments could have an influence on the stability and aggregation state of particles. In addition, the hydrophobic characteristics of polystyrene NPs (~100 nm) could create less aggregation (a mean particle size of ~ 230 nm). Table 4 indicates that the presence of HA-coated 1% Cu-doped TiO\textsubscript{2} or polystyrene NPs could decrease viable cell amount by 1.5~3 orders of magnitude compared to that with 1% Cu-doped TiO\textsubscript{2} NPs. Moreover, it was observed that viable cells dropped about 50~100-fold in the presence of NPs (20 mg/L), which was possibly derived from the inefficient interaction between NPs and cells to cause a decrease of floc size.

![Figure 2. Images of Cu-doped TiO\textsubscript{2} NPs and cells after UV exposure for 2 hr. (A) \textit{M. smegmatis}; (B) \textit{S. oneidensis} MR-1; (C) \textit{E. coli}.](image)

<table>
<thead>
<tr>
<th></th>
<th>1.0% Cu-doped TiO\textsubscript{2} NPs (20 mg/L)</th>
<th>HA-coated 1.0% Cu-doped TiO\textsubscript{2} NPs (20 mg/L)</th>
<th>Polystyrene (20 mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No shaking Shaking</td>
<td>No shaking Shaking</td>
<td>No shaking Shaking</td>
</tr>
<tr>
<td>Log (CFU)</td>
<td>4.96±0.19 2.65±0.04</td>
<td>3.21±0.72 1.69±0.08</td>
<td>1.87±0.01 ~ 0</td>
</tr>
</tbody>
</table>

Application of nanoparticles for biotechnology

Finally, we also discovered some novel applications for biotechnology using metal NPs: 1) plasmonic nanoparticles can be used to tune light wavelength for improving algal photosynthesis; 2) nanoparticle can also be used for delivery of genes into microbes. In the first application, \textit{Chlamydomonas reinhardtii} growth can be enhanced by wavelength specific light-backscattering in the blue region of the spectrum from Ag nanoparticles. In the second application, we discovered that nanoparticle can assist DNA transformation under electronic spraying processes.
4. Collaboration Plans
The project team is now collaborating on further exploration of bioremediation capability of S. oneidensis MR-1 on metal oxide NPs after stress (such as UV) and microbial responses to NPs at a molecular biological level. The project team will continue to submit the proposals to McDonnell Academy Global Energy and Environment Partnership, as well as US and Thailand government agencies such as National Science Foundation (NSF) and Department of Energy (DOE).

5. Research Products Related to Nanoparticle Work

Publications

Conference papers

Reference Cited


Linking People and Nature: Winter Institute on Energy, Environment, and Development

Washington University
Tata Institute of Social Sciences
Foundation for Ecological Security
The Indian Institute of Technology-Bombay
Udaipur, Rajasthan, India
December 14-24, 2009
Linking People and Nature: Winter Institute on Energy, Environment, and Development

Gautam N. Yadama  
George Warren Brown School of Social Work, Washington University  
Subodh Wagle  
School of Habitat Studies, Tata Institute of Social Sciences  
Jagdeesh Puppala  
Foundation for Ecological Security  
N.C. Narayanan  
The Indian Institute of Technology-Bombay  
  Udaipur, Rajasthan, India  
  December 14-24, 2009

Introduction

With funding from the McDonnell Academy Global Energy and Environment Partnership (MAGEEP), Washington University and three other highly regarded Indian partners organized and implemented an interdisciplinary winter institute to examine issues of energy, environment, and development. The School of Habitat Studies at TISS, the Center for Technology Alternatives at IIT Bombay, and the Foundation for Ecological Security (FES) were key partners with the Brown School in the design and implementation of the institute. The idea is to bring students, professional development practitioners, and faculty working in the areas of energy, environment, and sustainability to develop and deepen our understanding of the linkages among these facets. FES professionals and faculty from the three Academy partner universities developed real world case studies that illustrate the complex inter-relationship between energy, environment, and development along the rural to urban continuum. The goal is to advance our understanding and subsequent policy and program interventions in communities that experience problems that are the intersection of environment, energy, and poverty. Foundation for Ecological Security (FES) provided extensive access to these real world scenarios and using a joint institute mechanism, we developed three case studies and worked in interdisciplinary teams of students, faculty, and FES staff to further deepen our understanding and potential strategies to address the problem.

Students and faculty in these teams were from IIT-Bombay, TISS, and Washington University. It was both a challenge and enormous advantage to have a mix of engineering students from IIT-Bombay and Washington University along with graduate students from social work, architecture and habitat studies. Two students in the institute were undergraduates from Washington University. FES staff with several years of experience in program and policy interventions in the area of rural energy systems, rural-urban watershed development, hydrology, and in community-based development were integrated into each team. Udaipur in the state of Rajasthan in Western India was an ideal site for its relevance to energy and environment related issues in India, and for its potential in illustrating the complexity of sustainable development practice.
Background and Context

Energy insecurity of the poor in rural and peri-urban areas combined with rapid urban growth in developing countries has significant negative impacts on local renewable natural resources. Approximately 2.4 billion people around the globe are energy insecure; they lack adequate supply of energy, in the form that they need, and at a reasonable cost (Inter Academy Council, 2007). Bioenergy derived from wood and crop residue is the primary source of energy for these 2.4 billion worldwide, and accounts for 34% of final energy use in Asia (Hazell and Pacahuri, 2006).

Urban and peri-urban growth also drives the demand for bioenergy to satisfy new construction as well as traditional heating and cooking needs. Moreover, urban growth increases demand for other renewable natural resources – water. As demand for water increases, the response has been to draw from ground water even as poor management of surface water from urban expansion continues to lessen surface water quality and supply. These in turn put pressure on the local watersheds and the need for greater conservation of standing forests so that surface and ground water are being renewed at a sustainable rate. The implications of unrestrained urban growth on adjacent rural and peri-urban households that are dependent on biomass are many, and that too adverse.

There are two important characteristics of the relationship between rural energy use and renewable resources; the relationship is substantially complex and it is dynamic in nature. The dynamic nature of rural energy use and its relationship to renewable resources and complex nature of this relationship stems from various types of uncertainties that affect natural resources and households. Urban growth and the resource pressures introduced by such growth is a significant factor in places like India. Revealing the interactions between poor households, their energy usage and local renewable natural resources requires an approach that is able to capture complexity, while maintaining the scientific relevance of the data inferred from those interactions. Sustainability must include sustainability of human systems – individuals, families, households, and communities – as well as sustainability of the environmental systems on which they depend. A good understanding of the state of renewable natural resources is possible when we examine the biophysical aspects of a resource with the ways that humans use and govern that resource and the incentives facing users and managers. Such approaches allow for a better elucidation of energy and poverty nexus.

Framing the Winter Institute: Three Case Studies

The case studies provide sufficient context for those unfamiliar with the situation to understand the problem and its magnitude. The objective is to arrive at a well-defined dynamic problem, description of the prevailing explanations for its causes, and interventions and adaptations to the problem that either have been attempted in the past or are currently being considered by the community, FES, local and regional government.

The resulting set of case studies provide an entry point for subsequent research using multiple methods for studying complex systems surrounding energy, environment and development. The institute provided an array of methods including geographic information systems, participatory rural appraisal, and system dynamics to examine the inter-relationships between energy, environment, and sustainable development.
Theme 1: Reconciling community and household bio-energy needs with environment and wildlife conservation in Udaipur

Udaipur region is a forest-dominated landscape and for a very large section of the rural populace and for several urban households and establishments and peri-urban settlements, firewood from the forests is the primary source of energy used for cooking, heating water and for heating homes in the winter. For many of the poor households particularly from the tribal communities (indigenous peoples), the gathering and sale of firewood from the forests is a significant source of cash income. On an average, each tribal household consumes around 3-4 tons of firewood annually. This level of bio-energy consumption without a plan for renewing the resources has a huge impact on forests whether inside or outside of the protected area boundaries and eventually on the lives of the poor that depend on natural resources. Can efforts in eco-restoration compensate for the loss of forest biomass (firewood)? What role can efforts in energy conservation through the introduction of fuel saving devices play in reducing the pressure on forests as a source for firewood? How does one balance the imperatives of biodiversity and wildlife conservation with the energy and livelihood needs of a vulnerable populace?

Theme 2: Rural to urban linkages in water resource use: Catchment analysis of Udaipur

One of the main tourist attractions of Udaipur is the city’s cascading lakes built around the 16th century. The catchments of these lakes mostly lie in the Aravalli hills within which the city is nestled. Several of the catchments are now severely degraded with loss of forests and soil, and many water channels from the catchments to the lakes are either blocked due to an ever expanding city’s hunger for land or have become drains full of debris and garbage from the city restricting water flow and gradually choking the lakes. The tourism industry and several citizen groups from Udaipur city have been clamoring for increased water flows to the lakes. Damming of the waters of the Mansi-Wakal Rivers has been seen as a panacea to the woes of the empty lakes of Udaipur. A section of local civil society continues to be bitter about what they perceive as a loss of rural livelihoods due to the dam’s construction to cater to the city’s need to please the tourist and the urban populace of Udaipur. Even as Udaipur continues to expand, ambitious plans for the supply of water from its surrounding regions are being drawn up. Scant attention is being given to understanding the social and ecological costs of unsustainable urban growth on proximate rural environments and adverse impacts on the sustainable development of rural livelihoods that are dependent on renewable natural resources.

Theme 3: Local governance and natural resource management in Udaipur: toward sustainable management of energy and environmental resources

Indigenous tribal populations predominantly inhabit large areas of Udaipur district. Current legislative and policy proposals are keen to strengthen the role of local communities in the governance of natural resources. Along with resistance from state and local bureaucracies, these initiatives at decentralized governance are hampered by a lack of adequate capacity within local communities to fully capitalize on the potential of these decentralized initiatives. Attempts at perspective planning at the habitation level, building a committed base of local community leaders with a strong ethic and a keen understanding of the development issues of the region are now underway. The goal is to strengthen communities and their leadership to play a vital role in institutions such as panchayats (Village councils). In linking habitations to panchayats (and beyond at a landscape level) we may instigate appropriate models for rural development which
might eventually help realize the potential of forward looking legislation aimed at strengthening local governance of natural resource dependent communities.

Products from the Winter Institute

Each of the groups produced an initial draft paper for presentation to all participants and invited technical and government experts. Subsequently, students and faculty that participated in the institute have produced case studies for use at TISS and conference papers on environment, water, and energy. These case studies and papers have been useful to illustrate the thematic issues and educate the students and faculty participating in the institute. The three institutions will further deepen and refine the cases for use in our respective universities. Professor Parasuraman and others have proposed that the group should continue to work together and advance issues of energy, environment, and development issues as they influence rural and urban populations in the developing world. New collaborative projects between TISS and Washington University have been initiated because of the institute on Energy, Environment, and Development.

See Appendix for a sample of papers from this project including two papers presented at the International Conference on System Dynamics in Seoul, Korea.
References
Appendix A

Energy-Conservation Team: Gautam Yadama, Anand Rao, Rini, Allison Deal, Dan Conner, Rupam Kumar, Paroj, Snajay, Rajaratan, Sri Harsha, Rahi, Kalyan, and Shri Kumar

A Winter Institute Product that was further developed for the 2010 International System Dynamics Conference, Seoul, Korea

The Livelihood-Energy-Conservation Nexus:
Intervention strategies to promote conservation in rural villages located near wildlife sanctuaries

Gautam N. Yadama, Dan Conner, Allison Deal
Washington University in St. Louis
One Brookings Drive
St. Louis, MO 63130, USA
(yadama@wustl.edu or conner.dan@gmail.com)

Kumar Rupam
Foundation for Ecological Security (Udaipur Cell)

ABSTRACT: For poverty-stricken communities located near the Kumbhalgarh Wildlife Sanctuary, harvesting natural resources from forests within designated sanctuaries constitute a critical source of livelihood. Kumbhalgarh sanctuary meets household and market demand for fuelwood, timber, grassy fodder, and non-timber forest produce. Approximately 160 villages depend on this sanctuary for a variety of products and the sanctuary is being denuded at an unmistakable rate. This study utilizes marginalized community-based group model building and expert testament to trace and scrutinize local livelihood behavior patterns in order to identify routes of intervention. The resulting System Dynamics Model of village livelihood and extraction from sanctuary highlights employment, buffer zone management, and household energy efficiency as three potential routes that could directly reinforce conservation efforts and reduce sanctuary degradation without disrupting the livelihoods of the implicated communities. Strategies of intervention are developed and justified in this paper.

Keywords: Livelihoods, household economics, poverty, conservation, ecological modeling, natural resources, energy, fuelwood, cook stoves, field modeling, group model building, and participatory rural appraisal
Introduction

Forest and wildlife conservation goals of a state are often difficult to meet without the support of people who are dependent on the natural resources being conserved. Billions of people around the globe depend both directly and indirectly on forests for a wide variety of resources; forests contain natural resources that are fundamental to sustaining diversified land-based activities. In addition to preserving ecosystems, serving as carbon sinks, and providing several other crucial ecosystem services, forests are of vital importance to securing livelihoods of poor and marginalized communities. Widespread dependence on forests paired with society’s accelerating demand for land area is unmistakably affecting the condition of forests around the globe. From the once-vast rainforests of the Amazon basin to the flayed, charred tracts that remain in South Asia, human intervention in forests is evident. For example, an estimated 1.2 billion people worldwide still depend on fuelwood for heating and cooking purposes, and extract resources at a rate limited by what they can carry. India, exemplifies the constraints and difficulties of managing protected areas that are also populated by people.

Models of household and collective behavior under conditions of critical depletion of timber and other resources offer insight into potential areas of intervention to reverse resource decline. In this study, rural village resource usage and extraction practices are scrutinized for behavioral structures and feedback threads that directly affect household decisions that in turn impact forest resources inside and outside the boundaries of a wildlife sanctuary. Multi-disciplinary field teams of development practitioners, social scientists, and engineers embedded in Rajasthan, India undertook firsthand observation of these behavioral patterns, and gathered data to build dynamic models of people and sanctuary interaction.

This paper is structured in the following way: background details on the area under study; a description of behavioral patterns highlighting the livelihood-energy-conservation nexus; methods adopted for the study, including field modeling, participatory rural appraisal, group model building, interview and survey method, and expert interaction; results attained through the application of the field methods and critical issues driving the behavior of forest dependent communities and the present condition of the Kumbhalgarh Wildlife Sanctuary. Finally, the paper describes the System Dynamics Model and various simulations indicating sensitivity of energy, livelihood, and conservation variables and a discussion and recommendations for future work.

Background

This study was conducted in the Kumbhalgarh Wildlife Sanctuary (KWLS) and its peripheral villages of Padrada, Kyarakhet, Haila, and Pipalsari. Located between 25° – 25°40’ N latitude and 73°2’— 73°30’ E longitude, KWLS is situated north of Udaipur and covers 610.53km² (231.7mi²) in the Udaipur, Pali, and Rajsamand districts (see Figure 1). Its federal delineations are comprised of 600.18km² of reserved forest and 10.35km² of protected forest (231.7mi² and 4.0mi², respectively).

This wildlife sanctuary is an ecotone between the forests of Aravallis and the Thar Desert, serving as a barrier between forest and desert biomes. As a result, many rare flora and fauna are under constant threat of impinging habitat based on climate conditions. Additionally, the hills of this Protected Area (PA) serve as catchments for many rivers and nullahs, providing water for the human and livestock populations and irrigating the agricultural land in the Pali, Jalore, and Jodhpur districts.

The PA is comprised of rugged topography, with particularly steep hills in the Rajsamand and Udaipur districts. The forest tract consists of hill ranges between 300 and 4000 ft above sea level, including the highest elevation point in the Ranakpur region. Formed in the Archean eon, the Aravalli hill range is one
of the oldest formations in the world. The underlying rocks consist primarily of gneisses, biotite, schists, and limestone. The soil is predominately sand and sandy loam; vegetation coverage in these hills serves to bolster the low moisture retention consistent with this soil stratum. Rocky outcrops strewn with boulders are common throughout the region, as rain erodes much of the area not covered with significant vegetation.

**Figure 1: Map of Kumbhalgarh Sanctuary, Rajasthan, India**

![Map of Kumbhalgarh Sanctuary showing Villages and Roads](image)

**Flora**

The floral components of the PA are chiefly edapho-climate climax type; the forests of this area fall into the Category II Tropical Dry Deciduous forest classification (see Figure 2). Specific classifications identify the PA as SB – Northern tropical dry deciduous forest and C2 – Northern tropical dry mixed deciduous forest. Other sub-types within the sanctuary include DS1- Dry deciduous scrubs, E2- Boswellia forests, E5- Butea forests, E8- Saline Alkaline scrub savannah, and E9- Dry bamboo brakes (Champion and Seth 1968).

The subtropical climate of the region yields extremely hot summers and relatively moderate winters. The PA experiences three seasons: summer, monsoon, and winter. Summer typically lasts from March until June, during which temperatures can reach up to 44°C. Monsoon season generally starts in the last week of June and continues intermittently through September, contributing the majority of the average annual rainfall (~725 mm) within an average of 20 to 25 days of rain per year. Winter lasts from November to February; January is typically the coldest month. Moderate winds prevail from the southwest to the north-east during summer, and are reversed in the winter months. The region is subject to periodic and frequent droughts; adequate rains are typically received once in three years. Furthermore,
in recent years the frequency of drought has increased and the amount of annual rainfall has decreased; rains have become more erratic and less predictable.
Figure 2: Land Cover and Forest Types in Kumbhalgarh Wildlife Sanctuary

Map 4.1: Extent of different land cover/forest types in Kumbhalgarh WLS

Legend
- Villages
- Forest Blocks
  1) Dense Dry Deciduous
  2) Sparse Dry Deciduous
  3) Grassland/Desert Land
- Waterbodies

Elevation (metres)
- High: 1175.7
- Low: 359.1
Figure 3: Average Seasonal Rainfall

Figure 4: Average Annual Rainfall

Average Rainfall Over 14 Years in Hyla and Pipalsari (1995-2008)
Population and Demographics

The richness of natural resources in this landscape has enabled the communities to settle in this environment and secure a sustainable livelihood; over several centuries, many indigenous, pastoralist, and migrating communities have settled the area. For centuries, this population has been living symbiotically with the land, coexisting with the forests and diverse wildlife without significant effect or detriment. The society flourished due to set rules and systems based on the principles of subsistence and minimum interference driven by traditionally evolved management with socio-ecological-economic boundaries.

Currently there are 22 villages situated inside the Kumbhalgarh sanctuary and 138 villages located along the periphery. The population of these villages has increased gradually from 1960 due to migration resulting from diminishing natural resources in surrounding areas. However, this population growth rate has slowed since 2000 (See Figure 2).

Figure 5: Relative Change in Number of Pipalsari Households and Migration
(With Respect to 1960 level as perceived by village residents, formal data unavailable)
Families from communities within and bordering KWLS, traditionally cohabit in multi-generational homes. Polygamy is also accepted practice, thus it is not uncommon for the family of one patriarch to occupy several households. This filial structure has significant implication for increases in the rate of natural resource consumption, because population increases have translated to disproportionate increases in the number of households in the area, and resources are typically consumed on a per-household basis.

**Sanctuary Extraction**

The households in this area depend on the forests of KWLS and the surrounding areas for a variety of natural resources that sustain their nutritional needs and economic livelihoods. These products include fuelwood, timber for construction of houses, agriculture implements and other tools, non-timber forest products (NTFP), fodder grass, livestock grazing and foraging grounds, agricultural land area, and habitation land area. The area surrounding KWLS is not a designated buffer zone. A large area around the park boundaries is also forestland mainly designated as Reserve Forests by the government. The management of these lands is not strictly in the role of a ‘buffer’ to the park though local communities through Joint Forest Management are involved in the protection of some of the Reserve Forest areas outside of the park boundary.

**Issue Description and Reference Mode**

Historically, there has been a critical dependence of communities on forest resources in India’s arid and semi-arid regions. Unrelenting needs for timber, fuelwood, NTFP, and livestock foraging grounds have led to increasingly scarce forest resources. Consistent with this pattern, excessive extraction of forest products from KWLS has meant an increased rate of degradation of the sanctuary.

As observed by the communities in close proximity to the forest, forest cover in the region during 1960-80 was significantly dense but has since decreased. Research corroborates this trend; about 10% of initial forest cover remains today. Reasons for this degradation include increasingly infrequent rainfall, road construction, extraction of timber by the forest department a few decades ago, and increased deforestation due to local population growth.

Detailed biodiversity assessments by the Foundation for Ecological Security (FES) over the past three years across KWLS indicate sluggish forest regeneration. Decrease in rainfall in the area as well as extraction of tree reproductive assets has contributed to slower regeneration and recruitment rates. There have been attempts to mitigate this dependence on the sanctuary, but forest conservation efforts and rules governing sanctuaries ultimately interfere with the ability to increase availability of natural resources on which sanctuary inhabitants depend. Thus, these efforts have had little effect on the general deforestation trend.

At the core of protection and conservation are a set of interrelated factors that concern peoples livelihoods inside and outside the sanctuary. Energy insecurity and animal husbandry of households outside and inside the sanctuary is a significant aspect of pressure on the resources of the sanctuary. In a large way, household and other rural energy needs are significant drivers of extraction patterns in KWLS that over time have reduced the availability of fuelwood and timber, grass for fodder, and other non-timber forest products.
Livelihood – Energy Interaction

Multiple communities depend on KWLS to meet their energy and livelihood needs in the form of fuelwood, fodder for livestock, NTFP, and many other resources listed previously. These forest products are primarily used to meet household subsistence needs, however, a proportion is typically sold for cash or bartered in nearby villages. Furthermore, net fuelwood demand and frequency of forest product collection varies between villages, depending on levels of poverty, distance from the forest resources and other climatic influences. There is also an active trade of fuelwood (some of it bartered for buttermilk and the remaining for cash) between villages inside and on the periphery of the sanctuary and villages in some distance from the sanctuary. For instance, a large fraction of fuelwood collected from the sanctuary is sold in a nearby town, Sayara, where fuelwood resources have been exhausted due to excessive extraction from local forest areas.

Energy – Conservation Interaction

Growing demand for fuelwood due to increasing population numbers unmistakably affects forest resources, and the communities residing in close proximity to KWLS are aware of sanctuary degradation. However, these communities are un-equipped and/or unwilling to act to conserve this resource. For example, food is cooked on traditional, low-efficiency stoves; fuel-efficient or more complete combusting stoves are absent in the study area. Furthermore, certain villages have exhausted their natural surroundings and are nonetheless increasingly dependent on forest products from KWLS.
Additionally, fuelwood sales continue to be driven by demand regardless of perceived deforestation in the purchaser community or collection area.

It follows logically that external conservation efforts directly influence the ability of the affected communities to gather fuelwood to meet energy demands. Hence, increases in timber availability could supplement this fuelwood demand.

**Livelihood – Conservation Interaction**

Households within this community supplement their economic needs by gathering and selling products from within KWLS. Additionally, declining agricultural productivity and increasing population drive the need for more farmland to provide for higher economic and sustenance demands; since these farmlands are often forested areas that are cleared and converted to agricultural fields, encroachment within KWLS borders is increasing (the forest areas adjacent to the KWLS are being steadily reduced and park boundaries are also being contested by adjacent communities). At odds with these behavioral patterns, regulatory conservation efforts potentially undermine the economic interests of the KWLS community.

This situation has led to various efforts to design policy to support forest conservation without significant effect on the community economic and energy needs. One such policy design is through the formation of Village Forest Protection and Management Committees (VFPMC) by the JFM Program for management of Reserved Forest areas within village Panchayat boundaries. VFPMMCs protect specific areas of land designated for meeting livestock fodder requirements and requirements for other forest produce through a set of bylaws that govern the user regime of the village-protected forestland. This policy has been enacted with some success, although the protected land area is not sufficient to support the community herd in its entirety.

**Methods**

To understand the energy dependence of rural households on local renewable natural resources and the subsequent impact on forest resources of the sanctuary, we will use system dynamics computer modeling (e.g., Ford, 1999; Sterman, 2000) with FES staff, rural villagers and households using group model building participatory techniques (Andersen & Richardson, 1997; Vennix, 1996, 1999). System dynamics is a method for understanding the dynamics of complex social and natural systems in terms of the underlying reinforcing and balancing feedback mechanisms and their influence on the stocks and flows of a natural-human system. What distinguishes system dynamics is the combination of being able to involve multiple stakeholders in the development and testing of computer simulation models using group model building (GMB) participatory techniques (ibid).

This section gives an overview of the methods utilized in gathering data on the foundations and impacts of KWLS behavioral patterns and developing a system dynamics model mapping the Livelihood – Energy – Conservation Nexus.

**Field Modeling Approach**

**Participatory Rural Appraisal and Group Model Building**

The Participatory Rural Appraisal (PRA) method was utilized to develop awareness of the dynamic problem through firsthand descriptions of the system. In this method, information was collected directly from the involved community with various PRA tools specified below. The goal of this data collection method is to incorporate the knowledge and opinions of rural people in the planning and
management of development projects and programs; PRA tools facilitate collection and analysis of information by or for the community. Because this is a collaborative process, PRA actively empowers marginalized communities and helps to identify resource needs and sustainable use patterns.

- **Social Mapping**: Utilized to understand social dimensions and demographics, including settlement patterns, institutions, and social structures of the surveyed villages.
- **Resource Mapping**: Employed in investigating the various resources available, as well as their importance, specific locations, and usages at the village level. Resource mapping served useful in understanding the interconnections between different variables such as forests, agriculture, and water.
- **Seasonality**: Gathering and analyzing data on seasonal variations in terms of extraction of fuelwood, fodder, and NTFP.
- **Focused Group Discussions and Timelines**: Focused group discussions were conducted in the surveyed village to understand the trends spread over a period from 1960 to 2009. The major components covered under these discussions included population, livelihood, family size, rainfall, crops and agricultural productivity, livestock, water availability, migration, and forest degradation. These discussions helped to identify the root causes of trends.

In this investigation, the PRA method was employed to examine livelihood, energy, and conservation relationships within the surveyed villages in order to gain insight and accurately define the dynamic system. System dynamics software was then utilized to visually map behaviors and effects in order to simulate patterns in the system and test dynamic hypotheses.

One of the strengths of this field modeling approach is its highly iterative nature; hypotheses are created, tested, and re-engineered as long as community input and expert feedback are available. Field visits were spent evaluating community-specific hypothesis priorities, honed with subsequent visits, in order to better model behaviors and variable relationships. The results of these visits were utilized in group model building sessions involving domain experts and stakeholder representatives. As a result, the model structure remained fluid through the scoping and consensus building processes until the final moments of its synthesis, and was agile to discover influence and factors revealed with sequential iterations of PRA and SD group modeling (Costanza and Ruth 1998). As a result, final hypotheses accurately reflect the habits, preferences, and faculties at employ in the dynamic system, gleaned directly from the involved community.

**Data Sources**

**Household Surveys**
The interview and survey method was used to collect data at the household level in the surveyed village. Major focuses were energy sources and demands, livelihood dependence, land description, details of livestock and fodder demand, income sources and expenditures, and coping mechanisms, all of which are directly or indirectly linked with the forest. A stratified sampling approach was selected for the household survey— relatively well off and very poor households were selected to represent the diversity of the village.

**Community Group Discussions**
Throughout the course of this study, meetings were held with groups of village residents in order to address particular sub-domains of behavioral patterns as a supplement and/or confirmation of survey
data. Households were invited to send a representative to gender-separated meetings. The data gathered from this method provided insight into household behaviors and feedback structures that are valuable to building model confidence; discussions were seeded through an impartial translator to ascertain model substructure priorities such as usage of available resources, product collection patterns, perception of reference modes conservation feedback loops, future lack-of-resource awareness and behavioral change outlooks.

**Expert Key Informants**

Local knowledge resources were tapped in order to gain accurate insight to crucial behaviors in the Livelihood – Energy – Conservation system.

- **Village Household Economics:** Kesulal Meghwal (Field Associate, Foundation for Ecological Security). Served as KWLS community liaison throughout the project timeline, providing commentary on livelihood substructures and household decision processes.
- **Forestry:** Dr. Nihal Chandra Jain (Chief Conserver of Forest- Wild Life Wing – Udaipur division): Meeting was held to discuss the interlinking components of the livelihood and energy demands of the forest dependent people with consideration of forest conservation efforts.
- **Dr. Justus Joshua** (Wildlife expert and Manager – Ecology working with Foundation for Ecological Security): has conducted detailed biodiversity assessments in the KWLS over the last three years, and we engaged his expertise and understanding of ecological factors to triangulate findings from the field.

**Livelihood-Energy-Conservation Model**

The system dynamics model (VENSIM®) created from the mental and numerical data collected effectively maps the relationships between juxtaposed household livelihoods and degradation of the Kumbhalgarh Sanctuary (Forrester 1980). This model, comprised of eleven different views focusing on key themes, is a research-stage model intended to aid in analyzing policy-centric effects in order to adapt to eventual management tooling (Costanza and Ruth 1998). The overall relationship discovered is depicted in the following causal loop diagram, and is described herein.

*Figure 7: Overall Causal Loop Diagram*

[Diagram of causal loop with labels: Deficit, State/Health of Sanctuary, Product Sales, Product Collection.]

Deficit is the difference between expenditures and income, influencing household decisions on which- and to what extent potential income sources are pursued (Causal Loop B). Additionally, consequences of increased forest product collection are reflected in the State/Health of the Sanctuary. As this variable diminishes, less forest products are available for collection (Causal Loop R). However, whereas the balancing, deficit-decision loop operates on a human-decision dependent time scale, forest degradation is much slower; moreover, behavioral patterns indicate that Product Collection is affected only by diminishing supply and not perceptions of sanctuary degradation. Thus, a feedback delay in sanctuary health and product collection is observed, and deforestation is sustained. Because of the largely mental basis of the economic decision making, and the highly interlinked variability biological systems,
evaluation and mapping of these causal loops involves Ecological and Economic Modeling, the results of which are characterized in the following section (Forrester 1980; Folke 2006).

**Model Assumptions**
While constructing the model, assumptions were made for simplification and estimation purposes. These assumptions are utilized to create generalizations for the activities occurring in and around the sanctuary without sacrificing the accuracy of the structure of the model.

- The sanctuary would be in stable ecological condition if all human impacts were removed.
- Villagers do not have preference for collecting different species of timber for fuelwood.
- Aggregate amounts of timber, NTFP, and fodder masses dictate the state of the sanctuary.
- A household is of average size and collects average amounts of products from the sanctuary, disregarding seasonal collection rates.
- The maximum number of livestock in each household is three cattle and three buffalo.
- Rainfall is based on a yearly average and does not account for seasonality.
- Wage labor is available when needed.
- The same motivations lie behind participating in seasonal and permanent migration.

**Model Data**
The modeling process consisted of alternating data collection and model building activities. Survey results on livelihood and energy are depicted in the following table:

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Parameter</th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Number of adults per household</td>
<td>6.7</td>
<td>3 to 13</td>
</tr>
<tr>
<td>2.</td>
<td>Landholding (Hectare/household)</td>
<td>1</td>
<td>0.08 to 4.8</td>
</tr>
<tr>
<td>3.</td>
<td>Number of large cattle per household</td>
<td>4.4</td>
<td>1 to 10</td>
</tr>
<tr>
<td>4.</td>
<td>Number of small cattle per household</td>
<td>7.3</td>
<td>1 to 20</td>
</tr>
<tr>
<td>5.</td>
<td>Amount of fodder collected per year (kg/yr)</td>
<td>4600</td>
<td>1300 to 17000</td>
</tr>
<tr>
<td>6.</td>
<td>Amount of fuelwood collected per household (kg/yr)</td>
<td>5400</td>
<td>1800 to 19000</td>
</tr>
<tr>
<td>7.</td>
<td>Per capita collection of fuelwood (kg/year)</td>
<td>900</td>
<td>200 to 2000</td>
</tr>
<tr>
<td>8.</td>
<td>Kerosene consumption per household (lit./year)</td>
<td>34</td>
<td>0 to 36</td>
</tr>
<tr>
<td>9.</td>
<td>Amount of Jatropha collected per household (kg/yr)</td>
<td>81</td>
<td>0 to 650</td>
</tr>
</tbody>
</table>

**Ecological Modeling**

**Sanctuary Timber**
The variable Timber Produce represents how many kilograms of timber are in the Kumbhalgarh Wildlife Sanctuary at a given time. This amount is affected by its growth rate and the rate at which it is extracted from the forest. Timber growth rate is affected by multiple factors, both internal sanctuary states and external effects. The amounts of NTFP and fodder in the forest affect the growth rate of timber at different levels, indicated by Effect of Fodder in Sanctuary on Timber Growth Rate and Effect of NTFP in Sanctuary on Timber Growth Rate. Induced reforestation efforts, in both forms of planted seeds and saplings, increase the amount of kg of timber produce in the sanctuary. Maximum Timber represents an upper limit on forest growth, the most timber that can be in the forest given the size of forest and amount of resources available. Maximum Timber affects both timber growth and timber extraction. The timber extraction rate is affected by external factors from the sanctuary. The Fuelwood Collection
Rate has the greatest impact on timber extraction. Each village household consumes about 10 kg of fuelwood each day to use for cooking and heating. As the population grows, the need for fuelwood also increases, which increases the timber extraction rate. Timber extraction rate is also affected by the condition of the forests and other common lands surrounding the sanctuary. These lands moderate extraction of sanctuary timber by providing fuelwood resources. They provide alternative sources of fuelwood, thus decreasing the amounts of fuelwood extracted from the sanctuary.

Figure 8: Sanctuary Timber
Sanctuary Non-Timber Forest Products

The stock of NTFP in Sanctuary depends on the NTFP Growth rate and the NTFP Extraction Rate. Besides the Natural NTFP Growth Rate, the overall growth rate factor depends on amounts of other products present in the forest, including timber and fodder. The maximum NTFP represents a boundary that implies NTFP growth is not limitless, given fixed land area and amounts of resources. This variable affects both the growth rate and extraction rates of NTFP. The NTFP Extraction Rate is mainly influenced by the NTFP Collection Rate, which is a measurement of the total NTFP weight being gathered from the forest per year; this total weight is currently increasing each year. The adjacent forest areas provide a buffer that alleviates the amount of NTFP taken from the sanctuary by providing other fruitful areas for villagers to gather NTFP.

Figure 9: Sanctuary NTFP

Sanctuary Fodder

This view of the model shows the process causing the fodder from the sanctuary to deplete. In this model, both grassy and leafy fodder is combined to evaluate an overall fodder measurement. The fodder in the sanctuary is increased by the Fodder Growth Rate. This growth factor is influenced by multiple factors, including effects from other types of growth in the forest, most notable timber and NTFP. The natural growth rate of fodder also contributes to this overall growth, which is limited by Maximum Fodder, an upper limit on how much grassy and leafy fodder can be grown, given the fixed land and resources of the sanctuary. The fodder in the sanctuary decreases as fodder is extracted by grazing animals and villagers cutting trees for stall feeding. The forest lands outside the sanctuary play a role in determining the overall fodder extraction rate and serve as intermediaries between the people and the protected land.
The resulting ecological model substructure is a combination of these considerations of interconnected growth rates and produce states, represented in a series of table-lookup functions. This structure affords indications of Sanctuary Health as well as model-based analysis of conservation efforts and elicited effects. A conceptual representation of this model structure is shown here.

**Economic Modeling**

Kumbhalgarh village households typically generate monthly income from four main sources: selling Timber/Fuelwood, Non-Timber Forest Produce, and Livestock Products, and seeking Wage Labor opportunities. A household’s expenditures decrease the in-pocket money, which is typically spent on fertilizer or farming accouterments. Household Expenditures account for food that a household may need to purchase in a season with low-yielding crops that are not sufficient enough to supply the food demand of the household members, as well as small purchases such as medicine, dry goods, and other one-time purchases. The resulting Causal Loop Diagram serves as a conceptual map of household decisions in times of debt, when expenditures exceed income.
In times of surplus, village households may be able to save sufficient amounts to buy additional livestock. This Investment Purchasing behavior is depicted in the following Causal Loop Diagram, mapping the decision to spend saved funds on either cattle or buffalo, the preferred purchases in the Kumbhalgarh villages.
Livelihood Structure

The resulting model substructure mapping Kumbhalgarh village household economic decisions and behaviors is shown here. The four sources of income: Fuelwood sales, NTFP sales, livestock product sales, and Wage Labor are detailed in the following sections.

Figure 14: Livelihood
**Fuelwood**

Fuelwood, the major energy source of the village, is collected according to the household demand, approximately 10 kg dry wood mass per day. The amount of fuelwood present in the village depends on the timber collection rate and decreases according to fuelwood consumption and sales rates. Various types of cooking stoves consume different amounts of wood for a specified output, and more efficient stoves consume significantly less wood. Women, the main collectors, collect 20 kg of wood every other day in order to meet this energy demand, which is used for cooking and heating. The remainder is sold to neighboring villages, supplementing Household Income. Naturally, as the population increases, so do the heating and energy demands. It has also been shown that when households have higher monetary deficit, more fuelwood will be collected to sell in nearby villages. Fuelwood sales depend solely on the outside fuelwood demand; this product is a major source of income for many village households because many of the neighboring villages have completely exhausted their timber resources.

Timber extraction rates are also affected by the condition of the forest and common lands surrounding the sanctuary; high timber yield in these is observed to moderate extraction of sanctuary timber. Because fuelwood is collected from an area including these zones, they serve as an alternative source of fuelwood, thus decreasing sanctuary extraction.

*Figure 15: Fuelwood*
Non-Timber Forest Product Income

Most households in the village collect NTFP both to use at the household level and to sell as a supplemental income source. In the past many of these resources were much more abundantly present in the forest, but over the years, hyper-extraction has caused these resources to become scarce and some, non-existent. Historically, tendu leaves were also collected when in season and sold to nearby villages as a source of income, but have since vanished. Lacking income from tendu leave sales, the households needed to find ways to compensate to make up for this lack of income they once regularly had by extracting even more goods from the forest, both timber and other types of NTFP. Gum and wild fruits, including date palm, are collected from the sanctuary and consumed by the household. Honey and jatropha are collected specifically for sales in nearby villages. As the number of households increases, more of these NTFP goods are collected from the sanctuary, increasing the pressure on the forest.

Figure 16: NTFP Collection

Livestock

This view captures Livestock Income, Investment Purchasing, and Dung Production. The four types of livestock contributing to livelihood and income are buffalo, cattle sheep, and goats. Livestock income consists of animal sales as well as sales of buffalo and sheep products. The number of livestock also contributes to the amount of available dung, which is utilized to increase crop yield.
Figure 17: Livestock Income

Wage Labor

The wage labor model substructure to left illustrates the household’s decisions to participate in wage labor. The amount of household income from wage labor is determined by multiple factors, which often vary seasonally. Households with expenditures greater than income will opt to participate in wage labor activity, which in this model collectively evaluate permanent migration and seasonal work. Initial Deficit Amount indicates the decision basis as to whether the household chooses to participate in this type of work. As a household’s deficit increases, additional household members will begin to participate in wage labor to compensate for surmounting debt.
Fodder Demand

Products from sheep and buffalo, such as ghee or buttermilk, are sold at neighboring villages and contribute to a household’s income. Production of livestock products greatly depends on animal health, which is greatly impacted by fodder availability.

Fodder demand from the sanctuary depends on two main factors, the number of livestock in the village and fodder availability from alternate sources. Buffalo and cattle require grassy fodder, goats require leafy fodder, and sheep feed off of both types. Grassy fodder from the sanctuary is consumed as the livestock freely graze the forest. The leafy fodder requirement is met by branches pruned from trees and fed to the livestock.

Alternative fodder sources include Fodder Produced on Private Lands, JFM Protected Forest Plots, and Community Charagahs. However, the amounts of fodder grown in these domains greatly depend on rainfall. In years of low rainfall, more fodder is extracted from the sanctuary because of lower quantities of stall feeding fodder.
**Population**

As the village population grows, there is a higher demand for natural resources, most of which are extracted from the sanctuary. Although the population has been increasing, the average number of people per household has steadily stayed at eight family members for the past 50 years, indicating that the number of households in the village has increased.
Agriculture

This view of the model illustrates effects on agricultural yield, which plays a key role in the livelihood of the village because of the high-dependence on agricultural produce for food and livestock fodder. Maize is the most common annual crop, and in years of prosperous water availability and climate conditions for the year, wheat and chickpea will also be grown as a second crop. Other determiners of the amount of agricultural produce supply are land area and availability of dung fertilizer from livestock. Moreover, maize crop residue is an important source of fodder and villagers must resort to other fodder sources such as the sanctuary grounds after weak agricultural seasons. Agricultural Expenditures rise when crop yields fail to meet household demand, and food must be purchased.

Simulation Runs of Scenarios

A plurality of simulations was conducted with varied inputs in order to characterize system sensitivity to variable changes. The results of this analysis indicated two crucial influences on the rate of degradation of the sanctuary: expenditures and condition of buffer zones.

Expenditures

In this analysis, Other Expenditures (Rs) was varied to below and above the critical value at which total household expenditures (Agricultural Expenditures and Other Expenditures in aggregate) is equal to household income. These simulations simulate the KWLS household decisions that are made in order to supplement monetary supply in situations when expenditures rise. Situations as such could include
seasons of failed subsistence crops during which food must be purchased, or strict sanctuary regulation in which fees must be paid in order to gather forest products from within KWLS. These scenarios and the effects therein are depicted in the following figures.

*Figure 22: Household Income Impacts*

- In times of low expenditures (Expenditures Just Below Income), Household Income is sustained without alteration of behavior or collection rates.

- In times of high expenditures (Expenditures Just Above Income), Household Income must be supplemented by gathering additional forest products to sell.

- In times of expenditures above a level recoverable through additional forest product sales (Expenditures Unrecoverably High), Household Income is in steady decline.
**Figure 23: Timber Collection Rate Impacts**

- **Expenditures Just Below Income:** Fuelwood collection rates are sustained until household supplies are effectively saturated, and sales rate is lower than outside fuelwood demand.

- **Expenditures Just Above Income:** Fuelwood collection is increased to meet outside demand in order to supplement Household Income with sales. This soon diminishes as other products sales are similarly increased and sustained.

- **Expenditures Unrecoverably High:** Migration for Wage Labor is increased on a temporary basis, decreasing the number of product-collecting members per household. Thus, fuelwood collection is initially high, and erratic thereafter.
- Expenditures Just Below Income: Wage Labor efforts are sustained at a level allotted by outside factors such as National Rural Employment Guarantee Act.

- Expenditures Just Above Income: Wage Labor efforts are sustained at a level allotted by outside factors such as National Rural Employment Guarantee Act. Forest product based sources of income only are increased in order to supplement income.

- Expenditures Unrecoverably High: Migration for Wage Labor is increased on a temporary basis (per month) in order to inject Household Income with sufficient monetary resources with which expenditures can be paid. Livestock investment purchases are made when small, incremental saving efforts amount to afford livestock prices, in order to further supplement income. Debt is rampant in this scenario, and often three or more members of a household must travel to find work.
Figure 25: Fodder Grazing Impacts

- **Expenditures Just Below Income:** Livestock Investment Purchases are made early, due to availability of savings. Grazing within sanctuary is increased incrementally with each purchase, contributing to the degradation of the sanctuary.

- **Expenditures Just Above Income:** Livestock Investment Purchases are made when savings allow. Grazing within sanctuary is increased incrementally with each purchase, contributing to sanctuary degradation equally, albeit after a time delay.

- **Expenditures Unrecoverably High:** Migration for Wage Labor is increased on a temporary basis, and Livestock Investment Purchases are made desperately, as any potential source of income is exploited in order to supplement Household Income. Sanctuary degradation is highest in this case, because all forest product extraction rates are increased as much as possible.
**Condition of Buffer Zones**

Among the simulations in which conservation efforts and regulatory policy strategies were varied to maximum and minimum levels, Condition of Buffer Zones elicited the most impact on sanctuary degradation. Reforestation efforts did not indicate long-sustained influence on sanctuary degradation, nor did fodder policy enactments such as JFMs or Community Charagahs. Scenarios in which current Buffer Zone condition is improved and degraded are depicted in the following figures.

*Figure 26: Timber Extraction Rate Impacts*

- **Current Buffer Zone Condition (Baseline):** Timber extraction rate from within the sanctuary is outpacing natural growth rates. Deforestation is unmistakable and resources are being diminished to eventual zero availability.

- **Buffer Zone Degradation:** Timber extraction rate significantly outpaces natural growth rates. Deforestation is rampant and catastrophic.

- **Buffer Zone Improvement:** Timber extraction rates are more sustainable, as forest products collected are supplemented by availability outside KWLS boundaries. Deforestation is slowed, but remains an issue because total Buffer Zone land area cannot support forest product demand entirely.
**Figure 27: Timber Produce Available Impacts**

- **Current Buffer Zone Condition (Baseline):** Timber available in sanctuary is diminishing, as extraction rates are outpacing natural growth rates. Deforestation is unmistakable.

- **Buffer Zone Degradation:** Timber available in sanctuary is diminishing rapidly, as extraction rates far outpace natural growth rates. Deforestation is rampant and catastrophic.

- **Buffer Zone Improvement:** Timber available in the forest is more sustained, as forest products collected are supplemented by availability outside KWLS boundaries. Deforestation is slowed, but remains an issue because total Buffer Zone land area cannot support forest product demand entirely.

**Discussion**

**Model Based Insight**

This study reveals that, to a noticeable extent, KWLS village populations consider household economics to be of utmost importance. In times of debt, these households consider conservation efforts as subordinate to securing sources of income, and forest product collection rates reflect this behavioral diagnosis. In light of current climatic drought having reduced agricultural productivity, it is fairly certain
that poverty conditions will be sustained or will worsen in the foreseeable future; thus, sanctuary degradation is projected to continue.

This admission may seem debilitating to external conservation efforts, but taking economic consideration into account in policy design can potentially focus strategy on the most effective routes of intervention. Hence, it is an encouragement that KWLS product extraction rates will respond to village-based economic stimulus.

**Study Limitations**

- Time constraint: The study had to be conducted within a stipulated, compressed time frame.
- Human error: Substantial reliance on the verbal responses of the inhabitants is potentially inconsistent with actual behaviors.
- Approximations: Some data procured are based on approximations and appraisals made by experts. For example, absence of GIS mapping lead to estimated areas of collection.
- Language: Local translators potentially could have manipulated communication in the course of interviews and/or surveys.
- Variable measurement and quantification: Unobservable concepts, such as the state of the sanctuary, must be quantified through multiple variables, in this case total mass of timber, total mass of NTFP, and total mass of fodder in the sanctuary. These concepts must be quantified with appropriate units to best represent the directly unobservable idea in the system dynamics model.

**Strategies of Intervention**

**Wage Labor Availability and Buffer Zone Management**

First and foremost, supplementing household incomes has been shown to directly affect the necessity of KWLS village populations to collect forest products for sales purposes. In support of this hypothesis, the National Rural Employment Guarantee Act (NREGA) has triggered unintended positive impacts on sanctuary health, as guaranteed employment for members of the majority of maligned households affords secure, more sustainable alternatives to gathering forest products.

Thus, it is proposed to work to shift the general economic foundation from gather-and-sell based to a more wage-labor based economy by increasing wage labor activity. Outside of improving NREGA performance and implementation, this can be addressed by creating work opportunities through which household income streams can be fortified.

Since sanctuary regulation efforts are currently being undermined heavily, perhaps resources could be re-applied toward such work opportunities. If the intended behavioral response takes effect, these resources would be better utilized by indirectly eliciting conservation results.

Furthermore, promoting quality land resource management outside the KWLS boundaries is shown to be a panacea for deforestation. Plantation to meet timber, fodder, and NTFP requirements could effectively forestall sanctuary degradation; many indigenous, multi-purpose trees can be introduced for meeting demands of the forest-dependent households.

In combination, these strategies present a compelling potential design that directly addresses conservation necessity by utilizing behavioral patterns: employing village residents to manage and
maintain buffer zones. If local people are employed to cultivate carefully-chosen species with agricultural practices consistent with sustainability concepts, buffer zones would be transformed to product –and income- yielding farmland. Sustainable extraction from this land area would be an indirect conservation effort, and local management and maintenance would help to ensure the economic security of the area.

**Fuel Efficient Stoves and Alternative Energy Technologies**

Combustion percentages and wood fuel efficiency hold direct influence on rate of deforestation. Improvements to conventional chulha stove efficiency are simulated to immediately reduce timber extraction rates, translating to increased growth rates and general sanctuary health.

Additionally, alternative energy technologies have the potential to transform the traditional energy usage paradigm in effect in KWLS. For instance, solar panels were found to be installed in some of the households, powering light fixtures through a simple battery assembly. This a reflection of such implementation potential; solar radiation in the area is available for 10-11 months per year, and is already being used to sustain some energy needs on a small scale.

As a result of these considerations, it is proposed to distribute or to sell cheaply fuel-efficient stoves and/or renewable energy technologies as a direct alternative to excessive timber extraction. At the household level, scope for alternate energy devices such as solar photovoltaics, solar water heaters, solar stoves, and biogas heating/cook stoves can be widened significantly. For instance, these technologies could be utilized to irrigate agricultural fields and buffer zone cultivations, provide household lighting, and improve the health effects involved with incomplete-combusting stoves. They would also immediately affect fuel consumption and forest degradation.

**Future Work**

To move from the research and learning model stage to a more robust management tool will involve significant model analysis and testing. Fortunately, with the significant support from the Foundation for Ecological Security, a local natural resource management stakeholder, current policy and subsequent effects can be analyzed for behavior verification and model confidence building. Only after extensive model based analysis of current policy can the model be utilized to make better-informed policy decisions based on adaptive resource management strategies. (Costanza and Ruth 1998; Grumbine 1994)

Using the current research model and the results of this study as an outline, a second study of these energy-livelihood-conservation connections is anticipated to take place in the summer of 2010. The goal of this additional field work is to further refine the current system dynamics model and gain a better understanding of the trends behind these complex relationships. Acquisition of additional data will also aid in testing the model to ensure that it accurately represents the activities taking place in the village and the state of the sanctuary.

Given the project scope, the results of this study offer an accurate depiction of the Livelihood – Energy – Conservation Nexus, however, we posit that additional data would be beneficial to the model accuracy. This entails widening the project scope to include the following:

- Labor migration preferences
- NREGA Performance Data
- GIS-Vensim Complexity

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• Forest fire frequency and effects
• Biological species-specific interrelationships
• Climate change effects

References
Champion and Seth 1968
Appendix: Equation List

Livelihoods

Due to unreliable resource availability, KWLS households are forced to alter their behaviors in order to meet their economic and sustenance needs. Livelihood needs are met through many different resources, many of which come from the Kumbhalgarh sanctuary. In seasons of poor resource supply, these households may increase resource collection rates, diversify collected products, or sell previously obtained goods such as livestock.

Figure 28: Livelihood Sources

(030) Deficit=IF THEN ELSE((Income-Expenditures)<0, Expenditures-Income, 0)
Units: Rupees/Month

(048) Expenditures=Agricultural Expenditures+Other Expenditures
Units: Rupees/Month

(085) Household Cash= INTEG (Income-Saving-Expenditures,1000)
Units: Rupees

(133) Saving=IF THEN ELSE(Income>Expenditures, Income-Expenditures, 0)
Units: Rupees/Month

(134) Savings = INTEG (Saving-Investment Purchasing,0)
Units: Rupees
Fuelwood Collection

There is an increase in need for fuelwood by the resident communities as well as the communities further from the conserved areas. The population of sanctuary villages continues to increase, driving up the demand of timber, used as fuelwood for cooking and heating. Most of the timber resources outside the sanctuary have been depleted; currently nearly all of the fuelwood extraction is from sanctuary forest. Nearby communities not located in or along the periphery of the sanctuary continue to demand timber from sanctuary communities. Monetization of resources has led the local communities living in the vicinity of the protected forests to cut, transport, and sell fuelwood in the outlying villages, where communities are affluent and willing to pay for the resources. Brick kilns, hotels, and other businesses also meet their energy needs by purchasing sanctuary resources. The advent of road networks and transport facilities has accelerated the sales of forest product, making it easier to transport large quantities of materials further distances in less time. Approximate calculations reflect that 10% of the total fuelwood currently collected is sold in the local market, thus, both sanctuary villages and more distant villages are becoming increasingly dependent on resources from conserved and protected areas.
in Village/Average Sales Time)-Fuelwood Consumption Rate)<0, 0, (Fuelwood in Village/Average Sales Time)-Fuelwood Consumption Rate))
Units: Kg of Wood/Month

(081) Heating Energy Demand=Heating Energy Demand Per Capita*Population
Units: Kg of Wood/Month

(082) Heating Energy Demand Per Capita=30
Units: Kg of Wood/person/Month

(089) Initial Deficit=1
Units: Rupees/Month

(128) Outside Fuelwood Demand=250000
Units: Kg of Wood/Month

(107) "Male/Female Ratio"=0.5
Units: person/person

(088) Initial Average Wage Labor=4000
Units: Rupees/Month

(101) "Kg/Bundle"=20
Units: Kg of Wood/bundle

(155) Total CH Energy Demand=Heating Energy Demand+Cooking Energy Demand
Units: Kg of Wood/Month

Wage Labor Income

Many of the people living in villages in and around the sanctuary participate in wage labor to supplement the household income. Wage labor consists of both seasonal labor and permanent migration. Permanent migration occurs when a family member relocates to another region to work and send this earned money back to the family. Seasonal migration involves sporadic wage labor participation for short periods of time when additional income is necessary and work is available. This commonly involves payment for farming work in other villages, both distant and nearby.

(037) Effect of Deficit on Wage Labor=[[(-300,0),(-0,20000)),(-300,11200),(-200,11200),(-200,8800),(-100,8800),(-100,6400),(-0.001,6400),(0,4000))
Units: Rupees/Month

(080) Initial Deficit Amount=1
Units: Rupees

(161) Wage Labor Income Per Household=IF THEN ELSE(((Household Income+Savings)<0, Effect of Deficit on Wage Labor((Household Income+Savings)/Initial Deficit Amount), Initial Average Wage Labor)
Units: Rupees/Month
Total wage labor earnings per household

Other Produce Income

Collection of NTFP from the sanctuary contributes to the livelihood of the people. When present in the forest, small amounts of date palm and other fruits are collected strictly for household consumption. Honey is seasonally collected and exclusively sold at markets in nearby villages. This resource provides direct monetary income; none of the honey collected is consumed by the households. In past years, gum has been collected for household use, but is no longer available. Forest degradation has caused this resource to become scarce and even nonexistent in most areas. Likewise, tendu leaves, also commonly known as bidi leaves, were at one time collected and sold in neighboring villages. Large amounts of these leaves would be collected during their short two week season, significantly contributing to household earnings, but have since disappeared with forest depletion. The NTFP most widely collected today is jatropha, a drought resistant plant commonly used for bio-diesel production. Although resilient, this plant has extremely negative effects on soil quality.
Livestock Income

The total livestock population in the villages has decreased substantially due to deforestation. At one time, a typical household maintained 30-40 cattle. However, lack of fodder and water has led to a significant decrease in livestock population per household. Products from sheep and buffalo, such as ghee, are sold at neighboring villages and contribute to a household’s income. Production of livestock products greatly depends on animal health, which is greatly impacted by fodder availability. Households also use livestock dung as fertilizer for crops. Fewer animals results in less dung, making it more difficult to have high yielding agriculture seasons.
(009) Buffalo= INTEG (Buffalo Increase,1) 
Units: Head

(010) Buffalo Dung Production Rate=360 
Units: Kg of Dung/(Head*Month)

(012) Buffalo Increase=IF THEN ELSE( 
Maximum Number of Buffalo>Buffalo, IF IF THEN ELSE(Savings>(Buffalo Price*Head Increment),STEP(8, 1), 0), 0) 
Units: Head/Month

(013) Buffalo Milk Production=1 
Units: Kg/Month/Head

(014) Buffalo Price=4000 
Units: Rupees/Head

(015) Buffalo Products Price=300 
Units: Rupees/Kg

(017) Cattle= INTEG (Cattle Increase,1.5) 
Units: Head

(018) Cattle Dung Production Rate=210 
Units: Kg of Dung/(Month*Head)

(020) Cattle Increase=IF THEN ELSE( 
Maximum Number of Cattle>Cattle, IF THEN ELSE(Savings>(Cattle Price*Head Increment),STEP(8, 1), 0), 0) 
Units: Head/Month

(021) Cattle Price=5000 
Units: Rupees/Head

(069) Goat Dung Production Rate=1 
Units: Kg of Dung/(Month*Head)

(070) Goat Increase Rate=Goats/Goat Reproduction Time 
Units: Head/Month

(072) Goat Price=2500 
Units: Rupees/Head

(073) Goat Reproduction Time=24 
Units: Months

(074) Goat Sales=Selling Goats

(075) Goats= INTEG (Goat Increase Rate- 
Selling Goats,7) 
Units: Head

(135) Selling Goats=7/24 
Units: Head/Month

(136) Selling Sheep=1/24 
Units: Head/Month

(137) Sheep= INTEG (Sheep Increase Rate- 
Selling Sheep,1) 
Units: Head

(138) Sheep Dung Production Rate=30 
Units: Kg of Dung/(Month*Head)

(140) Sheep Increase Rate=Sheep/Sheep Reproduction Time 
Units: Head/Month

(142) Sheep Price=1650 
Units: Rupees/Head

(143) Sheep Product Production=1/12 
Units: Kg/Month/Head

(144) Sheep Products Price=60 
Units: Rupees/Kg

(145) Sheep Products Sold Per 
Sheep=Sheep*Sheep Product Production 
Units: Kg/Month

(146) Sheep Reproduction Time=24 
Units: Months

(147) Sheep Sales=Selling Sheep 
Units: Head/Month

(103) Livestock Income=(Milk Products Sold Per Buffalo*Buffalo Products Price)+(Sheep Products Sold Per Sheep*Sheep Products Price)+(Sheep Sales*Sheep Price)+(Goat Sales*Goat Price) 
Units: Rupees/Month
(117) Milk Products Sold Per Buffalo=Buffalo Milk Production*Buffalo Units: Kg/Month
(115) Maximum Number of Cattle=3 Units: Head
(080) Head Increment=1 Units: Head
(114) Maximum Number of Buffalo=3 Units: Head
(032) Dung=(Buffalo*Buffalo Dung Production Rate)+(Cattle*Cattle Dung Production Rate)+(Goat Dung Production Rate*Goats)+(Sheep*Sheep Dung Production Rate) Units: Kg of Dung/Month

Fodder Demand

Conservation Efforts: Community Charagahs

Charagahs are common pasturelands and forests that provide natural resources to community members. These charagahs are a principal source of fodder for livestock; animals freely graze these pasturelands year-round. However, nearly 40% of these communal resources are barren and ineffective due to over-extraction and poor environmental conditions. Managed by village panchayats, community members frequently use these areas that are critical to their livelihoods, but often neglect and deny responsibility for the condition of these lands. This view results in abuse and overuse of charagahs. Excessive grazing inhibits fodder regeneration, and overcutting trees and shrubs causes soil erosion. The condition of these mismanaged community lands significantly affects amounts of fodder extraction from the sanctuary. It has been observed that the more fertile charagah lands available, the less the village members will have to resort to extracting natural resources, most notably fodder, from the sanctuary.

Conservation Efforts: Joint Forest Management Protected Plots

Joint Forest Management (JFM) protected plots were created to alleviate pressure on the sanctuary as well as meet livelihood requirements of local people. These areas are governed by combined efforts from local communities and state forest departments. Agreements between the people and the government allow the local people to become involved in conservation efforts and become aware of conservation concepts. JFMs also provide additional labor opportunities and as well as fodder and NTFP resources, helping contribute to villagers’ livelihoods.

(011) Buffalo Fodder Demand=120 Units: Kg of fodder/(Month*Head)
(019) Cattle Fodder Demand=780 Units: Kg of fodder/(Month*Head)
(071) Goat Leafy Fodder Demand=300 Units: Kg of fodder/(Month*Head)
(139) Sheep Fodder Demand=30 Units: Kg of fodder/(Month*Head)
(141) Sheep Leafy Fodder Demand=60-Sheep Fodder Demand Units: Kg of fodder/(Head*Month)
(049) Feed Processed per Kg Wood=1 Units: Kg of fodder/Kg of Wood
(050) Feed Processing Energy Demand=Processed Feed/Feed Processed per Kg Wood Units: Kg of Wood/Month
(052) Fodder Collection Rate=Grazing Within Sanctuary+Leafy Fodder Demand Units: Kg of fodder/Month
(056) Fodder Produced on Private Lands=Effect of Rainfall on Fodder Growth(Yearly Rainfall/Initial Yearly Rainfall)*Max Private Lands Fodder Units: Kg of fodder/Month
Agriculture

The combination of agricultural productivity decline and human population increase has amplified the need for farmlands, which are often created by clearing of conserved areas. Maize is most commonly grown, with wheat and chickpea as a second rotational crop in years with ample water resources. Maize crop serves as a staple food source, and crop residue is used and processed for animal fodder. In years where agricultural yield fails to meet food demand, a household must resort to purchasing food, which increases expenditures. In order to prevent deficit, households turn to other income sources, many of which involve extraction of sanctuary products. Agricultural yield is a sensitive variable changing from year to year that has the potential to cause cascading effects on a household’s income and livelihood state.

(001) Agricultural Expenditures=
(Food Demand per HH-(Maize Produce+Wheat Produce))*Agricultural Food Price
Units: Rupees/Month

(002) Agricultural Food Price=8
Units: Rupees/Kg of Ag

(003) Agricultural Land Area=1.5
Units: Bigah

(004) Agricultural Yield=Effect of Dung on Agricultural Yield(Dung/Initial Dung)*Effect of Rainfall on Agricultural Yield(Yearly Rainfall/Initial Yearly Rainfall)*Maximum Agricultural Productivity
Units: Kg of Ag/Bigah/Month

(005) Maize Crop Residue per Maize Produce=0.0625
Units: Kg of fodder/Kg of Ag

(007) Grassy Fodder Demand=Buffalo*Buffalo Fodder Demand+Cattle*Cattle Fodder Demand+Sheep*Sheep Fodder Demand
Units: Kg of fodder/Month

(008) Max Charagah Fodder=0.6*1700/12
Units: Kg of fodder/Month

(009) Max JFM Fodder=0.4*1700/12
Units: Kg of fodder/Month

(010) Max Private Lands Fodder=300/12
Units: Kg of fodder/Month

(011) JFM Protected Forest Plots=Effect of Rainfall on Fodder Growth(Yearly Rainfall/Initial Yearly Rainfall)*Max JFM Fodder
Units: Kg of fodder/Month

(012) Leafy Fodder Demand=(Goats*Goat Leafy Fodder Demand)+(Sheep*Sheep Leafy Fodder Demand)
Units: Kg of fodder/Month

(014) Stall Feeding=Community Charagahs+Fodder Produced on Private Lands+JFM Protected Forest Plots+Processed Feed
Units: Kg of fodder/Month

Agricultural yield is a sensitive variable changing from year to year that has the potential to cause cascading effects on a household’s income and livelihood state.
Effect of Rainfall on Agricultural Yield:

\[(0,0), (1200,1), (300,0), (365,0.138), (425,0.688), (0.776316), (484,0.404, 0.929825), (528,0.44, 0.964912), (600,1), (675.229, 0.991228), (704.587, 0.938596), (748.624, 0.833333), (807.339, 0.688596), (855.046, 0.583333), (900,0.5), (1060.55, 0.210526), (1200,0)\]

Units: mm/mm

Initial Yearly Rainfall=1
Units: mm/Month

Maize Crop Residue Available=Maize Produce*Maize Crop Residue per Maize Produce
Units: Kg of fodder/Month

Initial Dung=1
Units: Kg of Dung/Month

Dry Season Water Availability=IF THEN ELSE(Yearly Rainfall>800, 1, 0)
Units: Yes/no

Effect of Dung on Agricultural Yield:

\[(0,0), (5400,1), (0.0,5), (450,0.75), (900,1), (1350,1), (1800,1), (2250,1), (3600,1), (4050,1), (4500,1), (4950,1), (5400,1)\]

Units: Kg/Kg

Maize Produce=Agricultural Land Area*Agricultural Yield
Units: Kg of Ag/Month

Maximum Agricultural Productivity=32
Units: Kg of Ag/(Month*Bigah)

Yearly Rainfall=650
Units: mm/Month

Wheat Produce=IF THEN ELSE(Dry Season Water Availability=1, Agricultural Land Area*0.2*Agricultural Yield, 0)
Units: Kg of Ag/Month

State of the Sanctuary

Evaluation of the overall health of the sanctuary requires observation of multiple factors. Forest density data alone is not an accurate sole indicator of the state of the sanctuary because other crucial factors such as regeneration rate cannot be construed. A few common indicators of sanctuary health include regeneration rate, seed germination, grass cover, forest density, species type, stage of species, seed viability, and food chain balance, which all interlinked and affect one another. Gathered field data affords a selection of these indicators, which affect the interconnected states of timber produce, NTFP, and fodder in the sanctuary.

The complex relationships between mass of Timber Produce, NTFP, and Fodder in the sanctuary all impact one another, as illustrated in the model below.
Sanctuary Timber

The raw amount of mass of timber produce in the sanctuary is affected by many variables, including presence of other forest products such as NTFP and fodder. Types of plants in the forest affect the growth rates of each other, as they compete for ground space, sunlight, nutrients, and other essential resources. Multiple species also reinforce the growth of each other, providing nutrients and attracting wildlife to help complete a flourishing ecosystem cycle. Increased amounts of fodder in the sanctuary slow the timber growth rate. However, higher amounts of NTFP in the sanctuary stimulate timber growth rates. As NTFP is extracted from the forest, timber growth rates will accordingly suffer. Although timber can be classified as a single product type and net timber mass typically serves as an accurate measurement of forest health, the presence of favorable and unfavorable trees, as well as observation of diverse classes of species also serve as effective indicators.
Conservation Efforts: Reforestation

The Foundation for Ecological Security (FES) has led a great reforestation effort to plant saplings and seeds of indigenous species in the surrounding forest and common lands with the involvement of local community institutions. Although these reforestation actions have contributed to forest sustainment, because the rate of biomass extraction exceeds reforestation rates, the current planting activities do not have the capability to counterweigh forest product withdrawal.

Surrounding Forest and Common Lands

Designated protected areas surrounding the border of the sanctuary alleviate pressure on the sanctuary. The presence of these clearly marked buffer areas has significant impact on the degradation rate of the forest. Typically enclosed by short stone walls to designate boundaries and prevent encroachment, these areas serve as cushions to reduce the negative impacts that the increasing population has on the sanctuary. By providing distinct regions to separate the sanctuary and the village lands, the presence of buffer zones decreases extraction of sanctuary materials.
Figure 33: Effect of Condition of Surrounding forests and commons (Buffer Areas) on Fodder Extraction Rate

Figure 34: Effect of Condition of Buffer Areas on NTFP Extraction Rate

Figure 35: Effect of Condition of Buffer Areas on Timber Extraction Rate

(035) Effect of Condition of Buffer Zones on Timber Extraction Rate([[0,0)-(10,10)],(0,1),(1,0)) Units: Kg/Kg

(041) Effect of Induced Reforestation on Timber Growth Rate([[0,0)-(100,10)],(0,1),(1,1.1)) Units: Kg/Kg

(042) Effect of NTFP in Sanctuary on Timber Growth Rate([[0,0)-(10,10)],(0.0001,0),(1.59021,1.6),(3.36391,3),(6.20795,3.6),(9.63303,4)) Units: Kg/Kg

(040) Effect of Fodder in Sanctuary on Timber Growth Rate([[0,0)(10,10)],(0.030581,4.43),(2.53823,4.16),(4.92355,3.4),(7.37003,2.2),(8.99083,0.8)) Units: Kg/Kg

(024) Condition of Buffer Zones=0.5 Units: Kg/Kg

(007) Area of Timber Collection=60 Units: Bigah

(087) Induced Reforestation=0.5 Units: Kg/Kg

(094) Initial Timber Produce=15000 Units: Kg of Wood/Bigah

(116) Maximum Timber=15000 Units: Kg of Wood/Bigah

(120) Natural Timber Growth Rate=(1+(0.02/12)) Units: 1/Month

(151) Timber Extraction Rate=Effect of Condition of Buffer Zones on Timber Extraction Rate(Condition of Buffer Zones)*Fuelwood Collection Rate*Timber Produce/(Maximum Timber*Area of Timber Collection) Units: Kg of Wood/(Month*Bigah)
Sanctuary NTFP

NTFP is a crucial part of the forest ecosystem, supplying diverse products for wildlife and other plants alike. These forest commodities from the Kumbhalgarh sanctuary include date palm, wild fruits, honey, gum, tendu leaves, and jatropha, and when present, are collected by people in the nearby communities. These products directly contribute to the livelihoods of the people; some are directly used by households in the community and others are sold or traded at nearby markets. As the forest depletes, less NTFP is produced, directly affecting critical livelihood resources. The amounts of NTFP present in the sanctuary are affected by multiple factors, most notably the amounts of fodder and timber coexisting in the forest. Increased fodder in the sanctuary slows the NTFP growth rate. Fodder and NTFP compete for nutrients and ground space. Aggressive grasses and shrubs can suffocate and oust NTFP plants. The presence of timber produce positively affects NTFP growth rate; as the amount of timber produce increases, so does NTFP growth proportionally increases as well. As timber is extracted from the forest for fuelwood, NTFP forest product growth slows.

Figure 36: Effect of Fodder in Sanctuary on NTFP Growth Rate

Figure 37: Effect of Timber Produce on NTFP Growth Rate
Sanctuary Fodder

Fodder availability is critical for managing livestock, which is a key contributor to livelihood. Households obtain fodder from crop residue, JFM forested plots, community charagahs, and private lands, in addition to collecting fodder from the sanctuary. Local people collectively protect defined areas to meet their own fodder requirement during the summer seasons, but allow livestock to roam freely within the federal boundaries during the rest of the year. Households send livestock, mainly cows, goat, and sheep, to graze the sanctuary for grassy fodder. Sheep roam the forested lands for grassy and leafy fodder, and goats consume only leafy fodder. Typically, livestock roam the forests during the day hours and are stall fed each night. Excessive grazing of these sanctuary lands over time causes the forest resources to deplete, which hinders the forest’s ability to recover and grow. Presence of NTFP has positive effects on fodder growth rate, but only up to a certain point. NTFP provides soil nutrients, attracts wildlife, and contributes to the overall state of the forest ecosystem, which in turn, affects fodder growth. At this stage, extraction of NTFP slows the fodder growth rate, directly providing NTFP, but reducing future fodder resources. If too much NTFP is present, fodder will not have room to grow and flourish in the limited grounds space in the forest. Similarly, as timber produce increases, fodder growth decreases. An increased presence of trees will limit the amount of sunlight on the forest floor, impeding grassy fodder growth.

Figure 38: Effect of NTFP on Fodder Growth Rate

Figure 39: Effect of Timber Produce on Fodder Growth
Figure 40: Grass Cover in Kumbhalgarh Wildlife Sanctuary

(005) Area of Fodder Collection=1
Units: Bigah

(033) Effect of Condition of Buffer Zones on Fodder Extraction Rate
Units: Kg/Kg

(043) Effect of NTFP on Fodder Growth Rate
Units: Kg/Kg

(046) Effect of Timber Produce on Fodder Growth Rate
(053) Fodder Extraction Rate = Effect of Condition of Buffer Zones on Fodder Extraction Rate (Condition of Buffer Zones) * Fodder Collection Rate * Fodder in Sanctuary / (Maximum Fodder * Area of Fodder Collection) Units: Kg of fodder / (Bigah * Month)

(054) Fodder Growth Rate = Natural Fodder Growth Rate * ((Maximum Fodder - Fodder in Sanctuary) / Maximum Fodder) * Effect of NTFP on Fodder Growth Rate (NTFP in Sanctuary / Initial NTFP in Sanctuary) * Effect of Timber Produce on Fodder Growth Rate (Timber Produce / Initial Timber Produce) Units: Kg of fodder / (Month * Bigah)

(055) Fodder in Sanctuary = INTEG (Fodder Growth Rate - Fodder Extraction Rate, Initial Fodder in Sanctuary) Units: Kg of fodder / Bigah

(092) Initial Fodder in Sanctuary = 200 Units: Kg of fodder / Bigah

(112) Maximum Fodder = 200 Units: Kg of fodder / Bigah

(118) Natural Fodder Growth Rate = (1 + (0.23 / 12)) Units: 1 / Month

Population

(125) Number of HH = Population / People per HH Units: person / person

(129) People per HH = 8 Units: person

(130) Population = 805 Units: person

Miscellaneous

(051) FINAL TIME = 100 Units: Month
The final time for the simulation.

(095) INITIAL TIME = 0 Units: Month
The initial time for the simulation.

(132) SAVEPER = TIME STEP Units: Month [0,?] The frequency with which output is stored.

(154) TIME STEP = 0.125 Units: Month [0,?] The time step for the simulation.
Dilemma of a Lake City

1. Introduction

Udaipur is the City of Lakes was founded on the eastern side of Lake Pichola and to present its development trajectory has been dependent greatly on the lakes of the city which make it a known tourist destination. In the exercise which we undertook, we have focused on the Udaipur’s urban water supply, whilst tracing the sources of water and their contribution to the consumption by people. Being a popular tourist destination Udaipur has faced paced urbanization and increasing influx of tourists every year, which has continuously put stress of the water sources of the city. There has been increasing scarcity of Water. The demand and supply gap has been increasing over time and the provisions adopted show a clear trend of shift on dependency on groundwater and external sources to augment water supply. The existing infrastructure for distribution system is inadequate to provide minimum required drinking water. This infrastructure is not able to carry existing 42 MLD supply – whereas city presently needs 88 MLD of supply. Due to uneven topography of city there are many low pressure points. The construction of a series of Dams has been sought as a panacea for all water problems, but there are doubts to the efficacy of these dams, and additionally such externalization of cost deepens the rural – urban divide. The city is also exploring PPP in distribution and management of water resources. But here the concepts of affordability, equity and the recognition of stakeholders need to be considered carefully. In this report, we have highlighted the emerging issues of water supply system in Udaipur city and concerns revolving around it.

1.1 Objectives

- To understand the history of water supply system in Udaipur and the change that has taken place over the years.
- To explore the factors that determined the changes and their implications for water supply system in Udaipur.

1.2 Output/ Methodology

The output of the study has been a comprehensive report which documents all the aforesaid topics. The methodology we have followed is applying different qualitative methods such as
interviewing, focus group discussions, house-holds surveys and oral histories. The primary data sources include different stakeholders such as the common citizens, government officials, farmers, and representatives from industries, commercial establishments. And the secondary sources include the Master Plans, CDP Udaipur, Project Reports, and Census Data.

1.3 Outline

The report is divided into seven sections. In the first section, we have described the objectives, methodology and limitations of the study. In the second section, we have highlighted the water supply system in Udaipur, especially focusing on the institutional arrangements. The third section focuses on understanding the different sources of water supply system and the emerging scenario thereof. The fourth section explains the problems and concerns of water supply system in Udaipur. The local people’s understanding about the water problem and concerns has been discussed in the fifth section. In the sixth section, we have made an attempt to identify the possible alternatives needed to be considered for the better management of water supply system in Udaipur. The future research work has been mentioned in the last section of the report.

2. Water Supply System in Udaipur: An Overview

2.1 Institutions for Water Supply and Management

The institutional set-up augmenting the water needs of the Udaipur city and its periphery include both state system and commercial (private) enterprises. The state system is primarily the public health engineering department (PHED). The government in India being a welfare state, the PHED is involved in accessing water, purifying and distributing the same to the citizens at nominal cost. The coverage continues growing with the government policy.

The commercial entities broadly include two groups. One set of enterprise include in individuals owning a water source (Well/ tube-well) who sells water to tankers (5000 litres) at about Rs. 50 and the tanker in turn sells the same at Rs. 150 to Rs. 200 depending distance to destination, seasonality, location etc. The other set of enterprise include individual, who have made investments for reverse osmosis (RO) and cooling plant. This set purifies and cools the water before bottling the same for sale only for drinking at Rs. 20 per 20 litre bottle.

2.2 Trends in Demand & Supply in Recent Past

Source of water to Udaipur city are its various lakes viz. Pichola, Fatehsagar, Jaisamand, and ground water from Jhamar Kotra mines and local tube wells & bowaries. During last few years, Udaipur has faced drought years and experienced severe shortage of water. To cater to increasing water demand, diminishing yield of existing water sources, it is planned to tap more sources of water and augment existing sources. The water demand as in 2001 was 72 MLD (based on 130 LPCD normal households and 70 LPCD slums, considering 15% population lives in slums and rest 85% is normal households, moreover requirement of industries is considered as given by them in detail). As against this demand of 72 MLD, present service level is only 43MLD. In 1987 Badi Lake was considered for augmenting water supply system of Udaipur, since Pichola Lake was almost dry. Nearly 5 to 6 MLD of water is drawn from Badi Lake when levels in Pichola and Fatehsagar lakes are very low. During draught year of 1988 an emergency water
supply scheme from Jaisamand Lake was sanctioned, which eventually got commissioned in 1995 for about 21.32 MLD. Another scheme was executed for utilization of ground water resulting from dewatering of Jhamar Kotra Mines. With consecutive drought years since 1996, ground water were taken into service in addition to the depleting surface water to keep survival service level, by supplying water on alternate days.

2.3 Institutions, Access and Sources
The changing political and economic scenario has led to change in the institutions and systems of management of water resource. This has also affected position of the stakeholders, nature and means of the access to water. The pre-independence scenario has the Mewar kings patronising the bawdis and lakes for drinking water and irrigation. The communities then, had a kind of cultural relations with water and thus acted as custodians of the natural endowments. But, the independence brought with it centralisation of state management, and therein came external imposition of needs. The policy makers felt that the growing needs of basic amenities will needs state intervention, as they will involve large capital investment. The PHED as an institution and the public water distribution system supplying through pipes and taps came into existence. The primary mandate of the same was to procure and distribute the water to the end users. The stakeholders until two decades after independence were more stable with nearly same set of water sources and end uses and users. The cycle of droughts in this semi-arid region had not affected the situation much. The vision of Mr. M.L. Sukhadia to set up Dewas (named Phase-I, afterwards) in 1969, which was completed in 1973 to meet future growing needs, was the only external source water for city, but of little criticality. But the city could not stand the drought of 1987-88. This led to accessing the Jaisamand lake water through pipes in 1990, albeit through pumping up for 60 km and a height of 300 metre, as an immediate relief. This year marks the water divide for Udaipur as water augmentation from outside sources with high costs set in. The setting in of urbanisation process had political incumbents think for external sources to augment the potentially scaling-up future demands, albeit without foresight for treatment potentials in immediate neighbour, as some stakeholders worried for ecology say. Thus, the Dewas Phase-II, III & IV were planned.

But, the changing political landscape had led to cooling down on this plan and constructing of Mansi-Wakal dam at Chandwas as the villagers say. The pumping of water from the dam started in 2008. But this has also seen lot of protests from the community, which saw only loss out of the project, especially those having fertile farmlands in the submergence area. They also say that the communities living downstream (beyond a mile from dam), even within Udaipur district has been affected by drying wells which they used to take second crop (maize). The implementation of the Dewas Phase II has been started. Though the submergence zone seemed to be very little and people living within the submergence zone are being taken away to other placed, there is very little democracy, debate and transparency as the community in Madri says. Luckily, the Akodra Dam has only one farmer’s land in the submergence zone. But the community in the nearby hill, through which the supply tunnel has been constructed, say that wells have started receding in one side, probably due to cutting of sub-surface streams. This way, the count of stakeholders to Udaipur water supply increased many fold.
2.4 Genesis of Private Players in Water Supply Augmentation

The exorbitant investment needed to operate and meet demands of water needs forced the govt to involve private players in harvesting, procurement, treatment, distribute water and bring efficiency in managing the systems. Thus private business players were involved in construction of Mansi-Wakal dam and drawing water from therein. In the same manner, such parties are involved in construction of Wakal (Phase II) dams and transportation system. The city administration is also exploring public-private partnership (PPP) in the distribution and management of drinking water in the city. The tender for appointing consultant for the same has been put forth. But, such intervention in this sector need through examination in terms of the affordability, equity, and the nature of the relationship. The following section outlines the sources of water supply system and in doing so, identifies the factors for the changes in the water supply system through public private partnerships.

3. Sources of Water Supply System in Udaipur

3.1 Lake

The ecology of lakes in the larger water system plays a key role in the transfer, distribution and use of the water across all sectors: social, economic, political and physical. All residents of the catchments of the lakes are stakeholders in the lakes in use and preservation, whether they take an active or passive role in the various actions that are changing the dynamics of the lakes. Lakes are used to recharge ground water, to draw water for domestic and industry use, and for recreation and identity of Udaipur.

3.1.2 History and the Lake System

Udaipur, known as the City of Lakes, is based around a system of interconnected lakes that have fundamentally been the basis of existence of the city over the past few centuries. It is the historic capital of the former kingdom of Mewar in Rajputana Agency. Lake Pichola, Fateh Sagar Lake, Uda Sagar and Swaroop Sagar in this city are considered some of the most beautiful lakes in the state, all man made, constructed between the 14th and 17th centuries by rulers of the areas, creating a paradise. The lake system in Udaipur arises out of the Berach river and its tributaries which form integral parts of the upper Berach basin. In all there are ten major lakes that create this system. Three lakes in the upper catchment are Lake Badi, Chota Madar and Bada Madar which tie into six lakes lying within the municipal limits of the city: Lake Pichhola, Fateh Sagar, Rang Sagar, Kumharia Talab, and Govardhan Sagar. Downstream there is one final lake, Udai Sagar.

Badi lake, or Jiyan Sagar, is a man made, built about 500 years ago. Originally constructed to deal with the problem of famine in the area, today it is a storage reservoir situated about 15 kms north of the Udaipur city near the village Badi. The lake was named after Jana Devi, mother of Raj Singh. Jiyan Sagar is also known as Badi Ka Talab. Badi receives water from a seasonal river known as the Berach. Chota Madar and the Bada Madar are small lakes in the system that mainly feed water to the Fateh Sagar through the Chikalwas feeder known as the Madar Nahar.
Pichola Lake is among the oldest and largest in the city. Built in 1362, Pichhu Banjara ordered the creation of this lake during the ruling period of Maharana Lakha. Pichola is cited as being one of the most beautiful and picturesque lakes of Rajasthan. Located in the heart of the city, Pichola has been a main source of water and recreation for the people of Udaipur. The rivers Kotra and Amarjok feed the Sisarma river which is the chief source of water for the lake. The Pichhola is further known in different parts of the city with different names in the form of Rang Sagar and Swaroop Sagar. Because the lake was constructed in pieces, each addition holds its own name as each lake flows directly into the other without a river or canal.

Rang Sagar and Swaroop Sagar are both additions to the Pichola Lake. Rang Sagar provides the water connection between the Pichhoa and the Swaroop Sagar in the south and the Fateh Sagar in the north. On the eastern side of the Swaroop sagar is a masonry dam which has become a very convenient site for open defecation. Swaroop Sagar is a small artificial lake that was created by Maharana Swaroop Singh. The lake was subsequently named after him. It is also known as Kumharia Talab. Located behind the famous Jagdish Temple, Kumharia Talab is near Chand Pol adjoining Rangssagar. The lake was actually built to provide water to the people of Udaipur. Govardhan Sagar is situated at a distance of 10kms from Udaipur, and is also linked to Pichhola, receiving water from the Pichhola through a link canal.

Fateh Sagar is a medium sized lake in the northwestern sector of the city the lake lies just besides the entrance to Moti Magri Hill, north of Lake Pichola. This is also a man made lake built in the year 1678 by Maharana Jai Singh, but got its name from Maharana Fateh Singh, who later made additions to it. The lake is fed mainly by the Madar feeder system though it also receives overflow of the Badi lake. In 1994, the water vanished from the lake, but in 2006, the lake regained its water.

Udaisagar Lake is situated near the village Bichari, forming the last lake in the system in Udaipur city. It has previously been a strikingly beautiful lake. It is located at a distance of about 13 kms in the east of Udaipur. The construction of this lake started in 1559 and was completed in a six-year period by Maharana Udai Singh. The major source of water for this lake is the Ahar river which passes through the city and joins the river at the Sukha Naka Village. The lake then flows out to the Berach River, which is part of the larger Ganges system.

3.1.3 Pichola Lake and the Identity of the City

To understand the state of the lake ecosystem in the city of Udaipur, Pichola lake was selected as a case study, as this is the most central and the largest in the lake ecosystem. The lake has played a very central role in the lives of people in the past and continues to do so in the current situation. Historically the lake was an integral part of the lives of the people living in the city. A very major portion of the population of the city has physically located itself around Lake Pichola and will continue to build until a policy or a limit is placed on growth and migration. The existence
of bathing and washing ghats, around the perimeter of the lake indicate its use by the city at large. The changing ecology of the lake may result in social and economic changes, which may prove to be detrimental for the city and the culture of the Udaipur as a whole. Recently the lake remains fairly shallow even during heavy rains, and gets dry easily in times of severe drought.

Pichola is the main picture lake cited by tourists as the draw to Udaipur; in this it is a major economic driver for the city. Residents continue to rely on the lake for water, both through the pipe system, ground water recharge of wells and direct use of the lake as a source. This central lake exhibits patterns of growth and changing culture reflected in its use and levels of pollution. Though many people rely on Lake Pichola, it can be seen that it has been disassociated from the minds of many, and conflicts arise from its economic draw and need to be full and the impact that urbanization has placed on this natural resource.

### 3.1.4 Current Situation

The first impression Pichhola lake gives is that one has reached a place of great importance. The immediate perception is that the entire old city is mapped out around the Pichhola lake. It clearly gives off the impression that even hundreds of years ago this place held great importance and that it is the base of a great history. The ghats are situated all around the banks of the lake, which was clear evidence of its use as a public resource. It is evident that these ghats have fallen into a state of disrepair

Walking along the ghats one can see the very high levels of eutrophication that is present in the lakes. There is an overgrowth of both water Hyacinth and the algae, indicating very high levels of pollution in the lakes. In some places the lake has actually turned into solid land. Many temples were built and remain on these ghats. But a significant number of these temples have fallen into a state of disrepair or have been privatized. One hotel had previously been a temple, and has altered the shoreline of the lake to bring the appearance of water closer to the tourists. Large numbers of people bathe at the ghats and women wash their clothes along the lakefront. Some of these bathers and washers had come from localities around the lake which have scarce water supply, receiving water supply only two hours every in forty eight hours. Others had been coming here for many years and this use of the lake had become a part of their daily lives. They had maintained a very long relationship with the lakes.

The population residing around the lakes has increased considerably and covers a large part of the spectrum of socioeconomic class, as well as exhibits a mix of people from different communities and religions. The old city homes built around the lakes are slowly and gradually being converted into guesthouses or hotels. This is happening as a result of the great growth the tourism industry has experienced in the past few years. Even though the old city exhibits such rich cultural diversity, it has fallen into a state of disrepair. The piped water system was started by PHED to distribute water efficiently to homes, but gradually led to the abandonment of the
various step wells that existed in these areas. The state of the step wells has fallen off as they have been abandoned. Many receive contamination from the sewer lines, either through leakages into the ground water or direct flow of sewage from dumping into the wells. Some of these wells are owned by PHED which has been using them for the distribution of the water in this area.

Open drains exist everywhere and since the provisions for solid disposals are negligible, solid waste has found its way either into the lakes or into the open drains. There are open sewage lines in the city now, originally meant for storm water drainage, people openly dump directly into the street and allow the drains to carry it away. One highly cited fact by residents of the city is that there are leakages in the sewer lines laid in the bed of the Pichhola Lake, leading to high levels of contamination. New sewerage lines that were built as per the recommendations of NEERI in the area have construction defects which led to the back flow of lake water during the monsoon season. Even after repeatedly complaining to the authorities the people had failed to receive any relief from their problems, thus they started to find ways to fix it themselves. They had broken most of the sewer lines that had been laid out. Adding to this is the issue of illegal public urinals all along the lake and large amounts of solid waste being dumped.

When these lakes were built, the kings who had made these had allocated a step well to each locality, along with a rope well. The bad sewage conditions that exist in this area are contaminating the groundwater making it unusable, and by direct linkage the wells, all along spreading water borne disease to those who have no other source of water. In many places these step wells, known as the bavris in the local language, have been victims of urbanization. They have been filled or covered further reducing the sources of water supply to the lower classes who cannot depend on the pipe system for water. Wells that had been in use only a decade back have now become unusable. This happens as result of leakages from sewage pumping stations. One clear illustration of this is in the Chandpole locality around the lake Pichhola. Most of the hand pumps that existed in the area have been abandoned as a result of the contamination of the groundwater adding to the prevailing conditions of water scarcity.

There is a lot of confusion around the jurisdiction of the lake area. There are at least ten different authorities that claim some jurisdiction. It is currently owned by the Irrigation Department of Udaipur, PHED has jurisdiction over the draws that took place from the lake, the municipal parishad has some control over layer of the sewer lines. Also the newly formed Urban Improvement Trust has added to the confusion. Even though the lakes seem to be in such bad condition hardly anyone at the government level seems to be concerned about making conservation efforts.

### 3.1.5 Society and the Lakes

Udaipur is a region of rich history and culture. Over the many years it has seen many kings come and go. It has prided its history and continues to today. The natural resources have been the most
valuable possession of the region. But today the Pichhola lake, the central most and the most important lake of the entire ecology of Udaipur, is in bad condition. Understanding the importance of this lake in the social structure of the city one must ask what is it that led to the current state of deterioration of this valuable resource that once was the city’s pride and lifeline. What has brought about this metamorphosis within a decade?

Amongst the various causes for this degradation, apart from population growth, one can list the changes in the management of natural resources. Towards the middle of the nineteenth century, colonisation brought about privatisation and state control. In 1863, the Public Works Department (PWD) was created, thus withdrawing local control (of the village community) from johars and talabs. This marks the end of the commons, which translated into a considerable decrease in community resources through the loss of control. It also marks the end of the community’s interest for the upkeep of the common resources and the attitude of religious reverence for them, an aspect that maintains traces in folklore. The same process is witnessed, in a more vigorous way, during Independence which valued both privatisation and state control as the sole access to modernisation and progress, thereby further weakening the involvement of people with their natural environment. From the nineteenth century onwards and even more so since Independence, the Government has staked everything on the development of big basins. It thus encouraged projects linked to big dams and the large-scale development of river valleys, through centralised control, to facilitate irrigation. It has aided the construction of dams that would aid the development of various cities and act as sources of water to support the urbanization processes. One such example is the Manasi Wakal Dam. This dam has been solely built for the purpose of supplying water to the city of Udaipur. Not only this, many more dams are being built to augment the water resources within the limits of the city.

The larger role and importance of the State has lead to a disinvestment of society which has been bereft both of its control over resources and faith in the value of these resources. On one hand the state encourages privatisation of agriculture and on the other it wishes to play the role of the provider through centralised control of water and forests. Through this increasing bureaucratization, which inherently involves politicians who are alien to the culture of the region and ideologically removed from the residents, the process has perversely led to the usurpation of privileges, the creation of local mafias and the plunder of natural resources. The next generation seems to have totally come under an increased feeling of powerlessness if not a sense of defeatism. As was portrayed through the thoughts of many children in the city of Udaipur. They want to conserve and protect the natural resources that they had seen and lived beside all their lives, but they do not know how to do so.

It may be difficult to identify, in a precise way, the causes of the degradation of the spiritual environment; but one can bring out the historic traits of religion and spirituality compared to the practice today and observe the changes that have occurred. Rajput culture and the romantic chivalry of its ideology, as well as its legendary pride, crystallized in Rajasthan where the Rajput clans of Mewar and Marwar and the Bhatis of Jaisalmer successfully resisted the Moghuls who,
on the other hand, subjugated those of Gujrat, Bundelkand, Malwa and the vicinity of Delhi. This is a land where people are proud of their rich cultural heritage. Of the various kings and queens that have lived. They narrate their stories and how they contributed to the physical geography of the city. But today not every child is aware of how even the different lakes in the city were made, who made them, or why they were made. The lakes just exist today, an independent entity to which the people are gradually disassociating. This in turn had led to the condition that this lake exists in today. It has fallen into major disrepair and continues to deteriorate with every passing day. The temples are continually losing their significance, on many occasions being converted into private enterprises, which have further increased the gap between the people and holy natural resources. The great increase in the tourism industry has led to the great rise in population. The high levels of urbanization that the city has witnessed over the past few years have led to greater levels of pollution in the lake. The sanctity of water is being lost in this city. Even people who have used the lake in their earlier days now refuse to use the lake as they gain access to piped water.

Access of water to the different classes spanning through the city is skewed. Water now supplied through a piped distribution system is reducing the various interfaces where people would interact with Pichola. Today there are metal gates preventing people’s direct access to the water front. Bathing and washing on the lake, which the people of Udaipur have done for centuries, has been banned. All this has been done for the purpose of preserving and conserving the lakes. Yet the sewage lines that carry the liquid sewage across the city have fallen in disrepair and seemingly no one has actually paid any attention to it. There are open drains that empty their contents into the lake and no one will take any action. Bathers do not believe that they are doing harm to the lake. Their stories reflect the tradition of family and culture of bathing; they bath at a spot because their fathers did, and grandfathers before. While some are aware of the ban, they cannot understand how they are making an impact on the lake when it is compared to the amount of sewage and trash flowing in.

The city faces scarcity in terms of receiving water on a regular basis. According to some residents, they receive water only once in two days. Even then the water is available only for a period of two hours. The varying classes that exist around have devised different ways to get access to more water. The direct use of the lake, which today is seen in the worst possible condition, is practiced by the lower classes that have no other options for the use of water. Women at the lakefront use it to wash clothes, not only because water is scarce in their homes, but more importantly in the event that they miss the window of the pipe flow. Use of the water at the lake plays a vital role in the daily lives of these families.

The people living in city perceive the lake in various different ways, even though the common pride of its existence exists within all people of the city, very few are concerned about its deteriorating condition. They have stopped seeing it as a religious entity as a part of their social lives but now perceive it merely as a physical entity in whose preservation they do not have a role. In turn they are the major polluters. No individual consciously will try to pollute the lake.
Everyone knows what the lakes mean to the city at large but the lakes have stated losing significance to them. They less and less associate with them in the social and cultural ways, as the association becomes purely economic. And when an individual becomes a family and the family a community their actions and relationships with regard to the lake change, leading to the alienation of the lakes from the community.

Today, the folklore linked to the traditional belief system that is the specific expression of the spiritual resources, has been discredited to a very large extent (precisely for being folkloric and thus retrograde and obscurantist) during the decades of enlightened progressivism, it is thus difficult to rehabilitate its validity in the technological cultural integration regime which is prevalent nowadays. The people of Udaipur have reached this state of mind where they are unaware of the various repercussions these big projects can have on many thousands of people in the rural areas. They have reached a state of mind, where they believe that this is the only way to augment their water.

3.1.6 Economy of the Lakes

As part of the central image of the city of Udaipur, Lake Pichhola has grown as a major contributor to the economy of the city and its citizens through its tourist draw. The view, beauty and historic importance and construction of the lakes in the story of Rajasthan pull tourists to the city to experience the lakes. Tourist season ranges from about November to March each year, and has recently been estimated to equal the population of the entire city. This tourist population then over these months will double the need for water out of the lake, simultaneously expecting the water in the lake to be at its most pristine and high levels. Tourism is one of Udaipur’s largest industries. Many families and communities rely on the tourist draw of the city to maintain an income. These hoteliers, guest house owners, shop keepers, drivers and many others recognize the level and perceived quality of water in the lakes as their family’s economic well-being. This relationship with the lake is far less direct than those discussed previously.

Udaipur is a popular tourist destination both within India and internationally. It was named Best City of the World in 2009 by Travel & Leisure, and is also known as the “Venice of the East”, and the Kashmir of Rajasthan. Popularly it has been featured in many movies and television shows: many Hindi movies have been filmed in Udaipur, as well as Hollywood movies James Bond Octopussy and Darjeeling Limited. Octopussy features both the Lake and Monsoon Palaces, central pieces to the tourist draw today, and for many American tourists is the first view of the city. It is well known for its Rajput-era palaces. The Lake Palace, for instance, covers an entire island in the Pichola Lake. Many of the palaces have been converted into luxury hotels. Udaipur is as well a favourite marriage destination in India. Many celebrities, including film stars, were married in Udaipur. The popular culture and recognition of the city through film adds to its popularity among travelers. To keep up with the tourist season, increasing densities around the lake bring new construction of hotels, as almost 200 hotels have high occupancy in tourist season. The construction of a new hotel or the convergence of the family home to a hotel over the years has created 150-200 hotels and guesthouses that have high occupancy during tourist season.
On the heels of the rise in tourism popularity since the late 1980s, has been an increasing migration of the rural population to the city. As Udaipur established a level of primacy in the region there has been both a permanent migration from rural areas, both inside and outside of Rajasthan, as well as a daily migration pattern. Increasing density of people around the lake has lead to about 150 new housing constructions yearly within the city. Permanent city dwellers have added to the need for water, further drawing down the resource of the lake, while depending on it for work. These incompatible areas of dependence have lead to the current state of water conflict.

Hoteliers and guesthouse owners in the area understand the conflicting draw. Having depended on the piped system of water through PHED for a period of time, one guesthouse owner switched to well water. He found that his draw on the pipe system was costing more than he felt his guests were using and was overpaying for the service he was drawing. He constructed a new bore well on site, and has been using it for water ever since. Understanding that both the pipes and wells are dependent on the water of the lake he has established his guesthouse as “zero waste” and has gotten a positive response from tourists who stay with him. On several occasions he indicated that the well water would be contaminated from the back up of sewer and his links to water would become none.

A larger hotelier has expanded his industry over the years, and relies on four pipe connections to maintain his water draws for the hotel. Understanding that the continued presence of tourists is key to his continued success, he and others in a local area came together to help clean up the area around their hotels and homes. They maintain a street sweeper to pick up trash, a guard to keep out undesirable people, and other such clean up efforts. He relayed a story that while in the process to get the area clean and maintained the group had to work with the local government for certain permits and permissions. On hearing that a collaborative initiative was going on, the local leader for the area confronted the group as a potential opponent to her position of power in the area. The group had to ensure that there was no threat of an attempt to appropriate power from her or run for office against her before they were allowed to move forward. Given the chance to help clean up the lake and create policies and monitoring structures for the maintenance and rehabilitation of the water, he indicated that he would be willing to join that effort, but that the concerns of government officials and the level of distrust and corruption would prevent any such work to ever happen on a citizen level. Therefore the effort to clean and maintain Lake Pichhola lays squarely on the shoulders of the government.

3.1.7 Ecology of the Lake

Lake ecology in a system has an important balance to maintain that works to ensure quality of water and biodiversity in terms of plant and animal life that is used to gauge a level of wellness in water. Lake Pichhola is influenced by both the urban area directly surrounding it and the inflow of water from various feeder watersheds and the direct pumping and proposed pumping of
Pollution from the surrounding area is created from many factors, but the most obvious would be the population numbers and growth of the city as previously discussed. Sewer systems and solid waste are also linked to tourism the way the pull of water from the lake is, with more people in the city over the tourist season, there is an increased output of both sewer and solid waste over this time period yearly. The overall increase of population and the increasing density of the city through upward construction has created an output that is increasingly high in footprint compared to what had previously been seen in the city walls.

Previously there was a solid waste collection system in the city. As the population grew, there was a change in solid waste management practices that the people were to adapt to. Now, while there are dumpsters and trash collection sites around the city, many people do not use them as they are designed. Often trash is tossed beside the collection bins instead of inside of them, and this is not collected when trucks do come through to pick it up. Stray dogs in the city also will open these bags and go through them for food. As this occurs the waste gets spread out over the streets and will end up in the lake itself. While some waste is biodegradable, stray dogs and homeless cows eat most of this before it reaches the lake. Plastics, dyes, and chemicals that exist in what is thrown away are all adding to the pollution levels within the lake.

Sewer connection in the city has a clear variance to economic and social standing. Three points of sewage contamination into the lake are direct, via surface drain, and leakage of pipes. There is a common conception that much of the sewage in the lake is contributed to the problem by the large hotels amongst residents of the area. But, the large hotels and many of the smaller hotels and guest houses have maintained sewer connections because of the impact not having a sewer line would have on their success in the industry. Tourists they believe would never accept such conditions, and it would only take one incident to hit the internet and for their business to drop. The municipal sewer lines run under the lake out of the city. Maintenance on these lines has been said to be low such that there are cracks and leaks at joints in the lines that are allowing what is seemingly contained sewer to come into the lakes.

To residents of the city whose sewer system is not properly maintained another solution has been seen. As sewer systems have problems due to design flaws and lack of pressure in the correct direction, raw sewage backs up into the homes, allowing the simplest response to manifest: cut the sewer line from the street and empty household sewage directly into the surface drains intended for storm water runoff only. Since the storm water drains were constructed to drain directly into the lake, moving rainwater into Pichhola, the slopes of these drains now allows this sewer to flow into the lake as well. There are also those who directly deposit sewage to the streets and lake. Aside from faulty design of some systems, others are left with no sewage options from their homes. Open defecation and urination are prevalent in corners of the city and around the lakes at night. Overall, large amounts of sewage in the lake have lead to an imbalance chemically of the water.

The pollution of the lake also has an established link back to the social connections and relationships that people feel with the lake. As people see that the lake is being polluted they are more likely to continue to dump their trash and sewage into it. There becomes a level of social acceptance of these acts that perpetuates the level of solid waste and sewage collection in the
lakes. One shopkeeper in the old city expressed that while he used to use the lake, he no longer does and has not even gone down to the lake though his shop was only a few hundred feet from the lake front in a few years because it had become so dirty. This complete disconnect from the water means that he and others are not monitoring how others are using the water, again allowing the free disposal into the water, because there is no social consequence. Similar effects have been seen and documented within the theory of social disorder that support residents’ claims that the situation has gotten worse. Aside from the contamination of the lake itself, the lake’s role as a recharge source of the ground water is leading to these same pollutants seeping into the ground, affecting soils, plant life and contaminating well water still used by people. Ultimately contamination leads to closing the wells.

Inflows into the lake have also created an ecological crisis. The rate of urbanization of the catchments area has exerted pressure on the formal area of the city, but also the rural and surrounding areas. Impacts on the forest ecology by fuel wood draws for use and sale have led to degraded vegetative cover and soil conditions upstream from the lakes. During periods of heavy rain these soils are no longer able to absorb the amount of water they once did and top soils erode, flowing into the system along with the rain water. This has choked off smaller feeders and deposited large amounts of silt and sediment into the lakes themselves. Lake Pichhola has clear indications of this sedimentation. Parts of the lake are shallower than previously, and with evaporation after the rainy season, pieces of earth are evident. The greatest indicator is the presence of the water hyacinth. These plants feed off the rich nutrients of the top soil erosion to grow in the lakes.

The accumulation of pollutants and sediment in the lake are directly affecting the biodiversity of the ecosystem. One of the major issues is the level of oxygen dissolved in the water. Increases in nitrates and phosphates in the water from pollutants and sewage is choking out oxygen. The presence of the water hyacinth plants is contributing to the same. While on a simple level this does not seem like an issue outside of the dumping, a decrease in oxygen in the lake has greater impacts. Fish are dependent on oxygen levels. Without the fish the weeds like water hyacinth are ultimately left unchecked. Fishing, commercially and recreationally are pieces of the history and use of the lake. Commercial fishing may have begun to impact the population of fish, which contributes to the economy of the area, but the continued impact is on recreation. Residents are engaged in fishing less continuing to impact their relationship with water, and there is an impact on tourist use of the lakes for fishing as well impacting the economy. Ultimately, oxygen in the water would also on its own work to combine with different chemicals to create benign compounds that would remove the harmful pollutants from the lake. The inflow of pollutants has crowded out this natural cleaning process.

3.2 Ground Water Resources

3.2.1 The Abandonment of the Sacred Bawdi and Emergence of Bore Wells
The city of lakes, Udaipur, has a culture revolving around water. Certain relationships with water are obvious, such as the case with lakes, other relationships are controversial as in the case of dams, however, one relationship is crucial to the livelihood and future existence of water in the city, ground water. Ground water makes up about 20% of the world’s fresh water and is vital for irrigation, domestic water use, industry, and most importantly for Udaipur, replenishment of the lakes.
Historically, ground water’s most apparent role was in terms of water supply from bawdis. A bawdi is a step well structure built in conjunction with temples to tap ground water for use while simultaneously regenerating the ground water storage. The bawdi was a caste-based common, sacred, water source serving a majority of the people’s water needs. This direct and very close relationship between the people and the source of water they utilized ensured that it continued to be maintained from both a structural and water quality perspective. However, with time came new technologies that distributed either lake water or well water directly to the home of residents. This initiated the subsequent disconnect that was to occur between the people of Udaipur and their personal water uses.

However, this disconnect from one’s water source did not occur on all levels of society, only those who had a residence where they could receive this water and pay the flat rate were able to adapt to this new technology. As the disconnect between the privileged and their water source ensued, the condition of the bawdis continued to decline, leaving those who could not afford to adapt to also abandon the bawdis in favor of other poor quality, common water sources such as the lakes, and later, community hand pumps and taps.

Although the social impacts became visibly apparent, the environment was simultaneously degrading with the bawdis. As these once sacred recharge structures became containers for trash and sewage, the groundwater, which supplied the lakes and crops, became contaminated. As time went on, residents continued to overlook the importance of bawdis as urbanization pressure lead the covering of bawdis to create space for more people and industry.

The new pipeline distribution methods proved to be unsustainable in light of the emerging water needs of the city. As industries expanded, tourism boomed, and the population of the city exploded, the limited water supplied through pipe connections (currently provided every other day for 2 hours) could not sustain the city’s growing needs. This increased demand led to the adoption of yet another technology by the privileged, bore wells. Bore wells are dug to give access directly to underground aquifers which store water. With no bore well regulation, people were free to dig wells to meet their personal water demands. This mass extraction from the aquifers situated below the city, paired with unmaintained recharge mechanisms (bawdis), put the city in dire ground water distress.

For example, The Maaji-ki-Bawdi is the only bawdi in working condition is located in the Chandpol area of the walled city. It has an average depth of 15-17 feet. Built almost 200 years ago, it was primarily used by affluent classes of the society, but was later opened to all people after the severe drought of 1986. Today it serves up to 1 lakh people daily. The Water Works Department has taken the responsibility of supplying water from the bawdi to the consumers in the surrounding 3 colonies by installing a nine horsepower pump which runs for 6 hours regularly. The 3 colonies in the vicinity of this bawdi rely totally on its water for their needs. The priest of the temple claims himself the owner of the bawdi and supplies the water to the Water Works Department free of charge. The residents however pay a flat rate for the water which is supplied for 2 hours every alternate day. They store the water by running motors which pumps the water into storage tanks. Before consumption, the water is purified by covering the supply
tap with a piece of cloth. A bill of Rs. 119 for residential consumers and Rs. 270 for commercial consumers is collected bimonthly.

3.2.2 Inadequate Aquifers
Although the adoption of bore wells is a technology used in many parts of the world, the adequacy of the aquifers under Udaipur city pose a unique dilemma. Udaipur is located in the Ahar River basin surrounded by the Aravali Hills. The aquifers in this area are characterized as hard-rock type structures, indicating that digging deeper into the ground does not guarantee the presence of more water, thereby limiting the potential water the aquifers can hold. Aquifers are recharged through the percolation of surface water to the aquifer. The primary porosity of the aquifer determines the degree to which the aquifer can absorb the percolated water. Hard-rocks, like the ones under Udaipur are characterized as having very little primary porosity, meaning that once water is extracted for the aquifer, the possibility of recharge is limited and possible only through secondary porosity (crack in the aquifer). With an incredibly high extraction rate, it is undeniable that without regulation the Udaipur aquifers will run dry and the possibility of recharging the aquifers to a usable level is nearly impossible.

Secondly, the aquifers are characterized as having low specific yield meaning that the amount of water that can be extracted by a unit volume of the aquifer is low. In the case of Udaipur, this means that although the aquifers under the surface are large, the amount of water than can be extracted from them is limited. Compounding this problem is the fact that the ease with which the aquifer will transfer water from one place to another, or transmissivity, is low. These characteristics mean that although bore wells can access water, the amount of water residents can extract is limited, the energy required to extract water is high, and the possibility of permanently depleting the supply is imminent. The characteristics of Udaipur’s aquifers put the city at great risk for groundwater depletion even before other social, political, and economic factors are considered. When the characteristics of the aquifers are paired with these human issues the city of Udaipur was labeled as a dark zone, or area with very little groundwater.

3.2.3 Deterioration of Groundwater
Many years ago, Priyadarsni Nagar was able to dig bore wells 150 feet deep and easily have access to groundwater, however, the same location today must dig bore wells 600 to 800 feet deep in order to access water. Despite drilling deeper many resident are not hitting water. The case of Priyadarsni Nagar exemplifies the current situation regarding the depletion of ground water in Udaipur. The city’s growing population along with the introduction of new industries has caused the rate of ground water extraction to skyrocket, however with no regulation regarding the digging of bore wells, there is no certainty as to how much water is being extracted and by whom-the fact simply remains that ground water levels are depleting at an alarming rate.

Aside from the simple extraction of water, the quality of the water being extracted is also decreasing. The characteristics of Udaipur’s aquifers have led the ground water to contain many heavy metals such as nickel and zinc leading to many gastrointestinal diseases including stomach and ovarian cancer. Although some people are able to afford filtered municipality water, the heavy metals in the water still have dire health impacts on the community. Apart from the characteristics of the aquifers contributing to poor water quality, improper sewage disposal, over and misuse of agrarian fertilizers and pesticides, and inappropriate industrial dumping are all also responsible for the contamination of groundwater. In cases regarding the over and misuse of
agrarian fertilizers and pesticides and industrial dumping, the cost of contaminating ground water is shirked onto a community which often did not contribute to the original contamination. The over and misuse of agrarian fertilizers and pesticides shifts the costs of contaminated ground water from rural areas to urban areas whereas the dumping of industrial waste shifts the cost from urban areas who are creating the waste, to rural areas which have to cultivate crops from the contaminated ground water.

Lack of maintenance of the sewage lines in the city has caused sewage to contaminate the ground water. For example, in the old city, the municipality run sewage lines became so ineffective, that sewage began to back-up into the homes of people. In order to avoid this backup, residents cut the sewage pipes from their homes, dumping sewage directly onto the street. This sewage not only contaminates the lakes, but also seeps into existing water pipes and wells, further impacting the health of the city’s residents.

Concurrently, as the quality of water in the city diminishes, so do the bawdis. A man residing in Chandpole commented that his area step well was used for many years to serve the needs to the people in the surrounding area and even sustained through a drought, however the construction of a sewage pumping station next door backed sewage up into the well making the water and the structure unusable.

3.2.4 Socio-Economic Drivers – The Impact of Creating Two Water-Use Classes

Although bore wells became a staple in most homes, the costs associated with digging, operating, and maintaining these bore wells perpetuated a disparity between the privileged and underprivileged. The initial cost of digging a bore well is at least Rs. 22,000. This large initial cost is then followed by a consistent operating cost associated with pumping water out of the bore well and into a tank. Today, as ground water becomes more scarce, bore wells are needed to be deepened at nearly 800 feet, which is in great contrast to the previously dug 100 foot bore wells. Lastly, upkeep of the pumping motor and pipe system are periodic expenses, which are also necessary in order to maintain a bore well. The privileged class typically can afford to have the luxury of a private bore well whereas the under privileged usually depend on common water sources.

Furthermore, the aforementioned decrease in the quality of water has pushed the emergence of another industry in Udaipur, the water purification industry. Reverse osmosis (RO) and other marketed waters are further driving the use of ground water. Although one can argue that the RO system simply filters the ground water individuals would be pumping regardless, there is a great amount of water gone to waste during the process. For every 2600 liters pumped for purification, nearly 1600 liters are deemed unusable and go to waste. As the quality of ground water decreases there is increased demand for purification systems such as RO putting added pressure on the already depleting ground water supply. While the privileged can afford these health-preserving services, the underprivileged cannot afford such facilities.

In the case of the Suraj Pole Gate slum, residents used one of two poor quality water sources: a hand pump, or municipality regulated bore well and tank system. Both water sources contain visible residue, which undoubtedly impacts the health of the residents consuming this water. The
story of Mirabai, a woman living in the slum with her nine children and husband, clearly outline
the effect of poor water quality and availability for those that cannot afford private water sources
and purification systems. Mirabai’s husband suffers from an amebic disease affecting the left
occipital lobe of his brain, which occurs when an amoeba, transmitted through water, infiltrates
the body via fecal-oral transmission. The presence of this amoeba is usually a characteristic of
poor hygiene and water contamination. As the sole income earner, his disability has stunted the
little income the family has sustained on, and now Mirabai faces the heart-wrenching dilemma of
using her minuscule income to buy medication for her husband or feeding her children.
Residents of the slum report that despite repeated appeal to officials, little has been done to
address the poor quality of water in area.

3.2.5 Actors Affecting the Ground Water Environment – Udaipur’s Largest Industries

The marble industry is one of Udaipur’s largest industries and a user of ground water. In the case
of a local marble plant, water drawn for the on site bore well is used for marble cutting, and then
filtered for reuse. Due to this reuse of water, the plant places minimal burden on ground water
levels, however, depositing of the marble slurry in Pratap Nagar is affecting the quality of the
ground water of the area and severely disturbing the natural environment. Despite these adverse
effects, the UIT has permitted dumping in this area. There is evidence however that other marble
plants get water from tankers, thereby depleting ground water resources in a distant location and
it is also not confirmed that all marble plants have water reuse systems.

A second large industry in Udaipur is the hotel industry. In order to meet the water demands of
the nearly half million tourists that visit the area, hotels populating the city have dug their own
bore wells in order to overcome this demand burden. Although some of this water is consumed, a
great controversy lies in the uses of ground water for other luxury hotel facilities such as
maintaining a green lawn and providing swimming pools. It is often questioned whether it is civil
for hotels to use water in such ways when many people in the surrounding area are deprived of
this natural resource.

When looking out upon Udaipur’s famous, Pichhola Lake, a dark discharge can be seen along the
banks near the hotels. This dark discharge is sewage from the hotels and is the source of another
great controversy. Although the hotels do not actively dump sewage into the lake, leakage from
the pipelines is causing the hotels’ sewage to partially discharge into the lake. The controversy
lies in the debate as to who is responsible in addressing this issue. The hotels claim that it is the
municipality’s responsible to maintain the pipes so that sewage does not leak; whereas the
municipality claims that the hotels are partially responsible for maintaining the lake that sustains
their livelihood. Regardless, this sewage is not only contaminating the lake, but also the
groundwater.

The dire state of groundwater today can be attributed to many causes and the impacts of its
deterioration are visible among all sectors of society. Its preservation is crucial to the survival
and health of the people in the city; its sustainability is crux of all industries in the area; and its
preservation is vital to all water sources in the city.
3.3 Dams: Sources of City Water

In order to supply the city of Udaipur with water as well as support various local industries, a series of dams have been constructed and additional dams have been proposed. A brief history of these dams, as well as descriptions of the dams and the stakeholders involved in the construction process is detailed below.

Dewas Stage – I

Dewas I is the first of four dams proposed in the Dewas scheme. This dam is a masonry gravity dam that is 92 feet high, 300 feet long, and contains open channels that are 5000 feet long. The dam contains a 7360 foot long tunnel that connects the dam water to Lake Pichola, located in Udaipur city. This dam was completed in 1973 at a total of Rs. 103 lakhs. It was financed by the Public Health Engineering Department. On an average, the Dewas I dam supplies 122 Mcft of water to Pichhola lake annually (which is less than the 167 Mcft of water that was anticipated according to the dam proposal).

Jaisamand Dam

To meet the urgent requirement of water supply of Udaipur City in the drought years of 1986-87, it was planned to divert water from the Jaisamand Lake. As per the interactions with some of the residents of the city, this was to be done within five months. The cost of construction was estimated to be around Rs. 5 crores. However, the plan was commissioned only in 1995 for about 21.32mld water. The actual expenditure incurred was almost Rs. 25 crore. The Jaisamand Lake, being situated 338.55 metres below the level of Udaipur, water was to be lifted. The project requires 27.8 lakh units of electricity per year for lifting water through pumps and the pumped water to Udaipur city\(^1\). According to some of the unofficial sources, diversion of water from the Jaisamand Lake led to loss of water for irrigation in about hundred villages. Further, although the Dam was supposed to be only a temporary solution till the Mansi-Wakal or Dewas Stage-II was completed, this hasn’t been the case.

Mansi-Wakal Dam

The drought of 1986-87 led to a greater focus on drawing water from the rural areas around Udaipur City. The Mansi-Wakal Dam was proposed in 1989. It was argued that since the total diversion from Dewas II, III, IV after the construction would not provide adequate water to meet the projected demands of the city, another project was quintessential and suitable sites were to be looked at. As an alternative, Wakal stage I and II schemes were proposed for augmenting water supply to Udaipur city area. The project envisaged the construction of two dams, one at the river Mansi and other at Wakal valley having gross storage capacity of 990500.0lac litres. The average annual yield of Mansi Dam @2142.50lac litres/sq.km of catchment area was calculated as 2445512 lac litres and that of Wakal as 586093.0 lac litres with capacity of 862 mcft. The WAPCOS (Water and Power Consultancy Services) recommended the implementation of Mansi-Wakal in its report of 1990, stating that it had greater potential than the Dewas project. Although

\(^1\) Singh Sunita (2002). Water Management in Rural and Urban Areas, 177, 179.
the foundation stone was laid in 1989, the construction was completed only in 2007. The cost of the project was shared by the Government of Rajasthan and Hindustan Zinc in 70:30 ratios.

**Gorana Dam** – Constructed on river Mansi -Wakal River, near Gorana village at a distance of around 60 kilometers from Udaipur city. Water from Gorana dam is transported to Nandeshwar tank through a pipes and a tunnel and then in to Udaipur’s water supply system.

**Dewas Stage II Dam**

The proposal for the Dewas Stage II dam was submitted to the Government of India for approval in 1972 and is currently under construction. The dam located near the Akodra village in Jhadol tehsil, has a 350 Mcft capacity, and is linked to Lake Pichola through a 7.1 mile long tunnel and auxiliary reservoir near the Madri village. The cost of dam construction as estimated in 1970 was Rs. 4.85 crores. The purpose of this dam is to provide water for both the Zinc Smelter Plant at Udaipur and to supply water to the city of Udaipur. However, the proposal was shelved for a long time as a result of the ongoing power dynamics.

3.3.1 **Mansi-Wakal Dam: Economic Costs and Benefits**

The construction of dams in rural areas to supply water to Udaipur city has had different socioeconomic impacts for urban compared to rural residents. Through various interviews and discussions, the majority of city stakeholders (including hotel owners, city administrators, engineers, and city residents) conveyed that they perceive dam construction as positively contributing to their livelihoods. They stated that they believed that dams were the best method to augment the city water supply to provide for the drinking and livelihood needs of city residents. Furthermore, many of these stakeholders argued that they felt that the dams were fundamental to supporting the tourism industry, which is a primary source of revenue for the city. However, these perspectives often fail to incorporate the fact that dams are expensive to construct and that the stakeholders who propose these dams often underestimate their cost and overestimate the amount of water that will be supplied to the city. In most of the cases, costs were under-estimated and the water yields of the dams were exaggerated.

In contrast to urban residents, discussions with rural residents revealed that they felt that dam construction negatively impacted their livelihoods. First of all, the dam projects divert water away from rural areas to urban areas in such a manner that decreases the amount of water that is available for the rural people to use. In addition, dam projects can lead to the displacement of entire villages of people. For example, Mr. Ganesh Purohit from Jagran Jan Vikas Samiti (a community based group organized to protect the rights of villagers during the process of construction of Mansi Wakal Dam) reported that six villages (namely the Talai, Gadariawas, Mundawali, Chandwas, Gorana and Devas villages) were negatively affected as these villages lay completely in the submergence zone. In addition, another two villages (Malpur and Chechalya) were partially affected as some portion of their lands lay in the submergence zone of Mansi Wakal Dam. From these villages, nearly 6800 people (or 850 households) were displaced due to dam construction. Individuals from the displaced villages reported that they were allotted land to compensate for the loss of their private land but that no compensation was given for the commonly owned land of the village that supports livestock and agriculture. Since the livelihood
of people in these areas is directly linked to agriculture and animal husbandry, loss of agricultural and common land has had an adverse impact on the livelihood of these individuals.

3.3.2 Social and Psychological Costs

Displacement has also been shown to contribute to a number of social and psychological stressors. In the displacement process, individuals are often separated from their extended kin and social support networks. Furthermore, in moving to new lands, conflicts can arise between displaced people and the inhabitants of these lands if both groups compete for the same jobs and other resources. Additional misunderstandings and tensions can arise between the new and old residents if they come from different cultural backgrounds or traditions. The impact of the stress that results from being separated from the land of one’s ancestors should also be considered. While the authors of this study were unable to assess whether the individuals displaced during the construction of Mansi-Wakal were affected by any of these stressors, additional studies should be conducted to further investigate this matter. Besides, as plans for the Mansi-Wakal project were being drafted, the rural people who would be impacted by the dam were not consulted. Government officials only informed these individuals after the plan had been approved. In order to inform these individuals, these officials posted a notice at one location in the village instead of notifying each village member who would be affected by the project. This method did not take into consideration the fact that many village people are illiterate. Such practices demonstrate that the land acquisition process and notification practices should be revisited.

3.3.3 Environmental Impacts of Mansi Wakal Dam

Dam construction has been shown to lead to a number of negative environmental consequences. The diversion of the natural flow of water caused by dams has been shown to contribute to deforestation, loss of surrounding wetlands, as well as the disturbance of fish migratory patterns. This negatively impacts the ecological balance of the area. Furthermore, dam construction can alter water quality. Sedimentation often occurs such that certain minerals are trapped by dams and unable to travel downstream. This has been found to reduce the soil quality of downstream areas in a way that negatively impacts the agricultural activities of these lands. Increased sediment in the waters of the dam can also result in the growth of noxious flora such as water hyacinth. The quality of water can also be altered due to the pooling of water in dams. This pooling can change the temperature of the water such that it is cooler in the summer months and warmer in the winter months than it would be if it was located in more shallow bodies of water. These changes in temperature can also alter the flora that can be supported by the waters around the dam. No studies have been conducted to the knowledge of the authors of this paper to investigate whether dams in Udaipur area have led to these sorts of ecological changes, however, the prevalence of such ecological impacts warrants investigation of these dams.

As explained in one of the documents published by Jagran Jan Vikas Samiti, one of the key environmental impacts possible due to the construction of the Mansi-Wakal dam was the submergence of 4022 ha of land. This land contained over 2,50,300 trees, 31,500 of which were
older than 50 years old. The local people relied upon this land to fulfill a number of their basic needs. For example, the people extracted fodder, honey, gum, medicines, and seasonal fruits from this forest land. Furthermore, they relied upon the wood that the forest supplied for construction purposes and as an energy source for their heating and cooking needs. Additionally, wildlife such as tigers, black bears, sambhars, and panthers has been reported to live in and near these lands. The submergence of this land will affect the livelihood of the wildlife and humans that live in this area and will strain the surrounding forests as humans and wildlife are forced to look elsewhere to meet their needs. Such strain on the surrounding forests could lead to negative disruptions in the soil-vegetation balance which could contribute to erosion and deforestation.

Past studies have shown that the construction of reservoirs can lead to increased frequency of seismic tremors due to changes in rock pressure that results from the drilling processes and from increased water pressure. In areas that are already prone to seismic tremors, this disruption and added stress can trigger seismic activity. Such reservoir induced seismicity resulted at Lake Mead in the United States, Monteyard and Grandwall in France, Vajont in Italy, Contra in Switzerland, Kariba in Zambia, Kremasta and Marathon in Greece, Mangla in Pakistan, and Koyna in India. While few large scale reservoir or dam projects have been constructed in Udaipur district to assess the susceptibility of this area to reservoir induced seismicity, past seismic activity in this area (in 1882 Udaipur experienced seismic shocks and on January 23rd and February 17th in 1983 shocks were felt in Ekling which is located 20 km away from Udaipur) may suggest that this area could be prone to reservoir induced seismicity. Thorough evaluation of the geological landscape of this area should be conducted to assess this risk before additional dams are constructed.

Another potential negative impact that could result from Dam construction in the Udaipur region is an increase in the occurrence of waterborne diseases. A study conducted by the World Health Organization in 1983 titled “Environment Health Impact Assessment of Irrigated Agricultural Development Project” investigated 22 dams around the world (including the Nagarjun Sagar dam in Andhra Pradesh in India) and found that in the majority of cases, the prevalence of existing diseases increased and new diseases were introduced to the areas surrounding the dam. These diseases included typhoid, paratyphoid, food poisoning, cholera, dysentery, schistosomiasis, tapeworm well’s disease, poliomyelitis, diarrhea, and respiratory infections. This study also found that in India in particular, dam construction led to increases in the population of the species of the A. Vagus mosquito species, which is a known transmitter of malaria. Given this information, more research needs to be conducted to investigate whether dams in the Udaipur region contribute to greater incidences of waterborne diseases.

In short, the construction of past dams as well as the construction of Mansi-Wakal has proven to result in a number of negative social and environmental impacts for individuals living in rural areas. These impacts should be taken into consideration in cost-benefit analyses that are performed when a new dam is proposed.
4. Problems and Issues: Implications of change in water supply

The above description shows that Udaipur water supply system does not stand on a firm foundation, both in terms of quantity of supply and coverage of population. And, this situation is likely to deteriorate further. Following are the reasons:

4.1 Paucity of Source
All lakes are dependent on rains in their catchments. With variation in rainfall it has been experienced that availability of water from one or more lakes is negligible during peak demand period i.e. summers. From Devas I dam conveyance system of Pichola consists of river shallow natural drain. Therefore, in flow from Devas I dam is feasible in Pichola and Fatehsagar system only during rainy period or when drain is saturated. Otherwise, quantum of water received in Pichola Lake is negligible as compared to water released from Devas I dam. Similarly close conduits/lined canal system for in-flow needed from future proposed dam sites. Augmentation of source is also a major necessity. It has to be supplemented with network of raw water conveyance system, WTPs, CWRs and further networks.

4.2 Pumping Machinery and Conveyance Main
The MS conveyance main from Jaisamand to Dudh Talai is damaged due to weathering effects resulting in many leakages and sudden breakdowns. Rejuvenation of mains including its outer coating and placing more expansion joints is required. Similarly, most of pumping machineries and electrical mechanisms need rejuvenation to increase flow capacities and efficiencies.

4.3 Groundwater Depletion
Tube wells located in Kharbadia, Jamar Kotra, Kanpur areas draw water from a limited aquifer. It is part of old Ahad river basin, from centuries Ahad is a seasonal river, in-flow occurred hardly for 20-30 days in previous decades. Similarly, tube wells and bore wells located in city are dependent on water level in Lakes. Most of the tube wells have very low or negligible yield in summers when demand is heavy.

4.4 Treatment and Disinfections Facilities
Treatment facilities are scattered, proper inter-linking of these facilities is required. It is difficult to ride over scarcity problems arising due to paucity of water in any of 4 major surface water sources of city. Rejuvenation of old filters plants and improvement of disinfections facilities is also negligible.

4.5 Inadequate Distribution Infrastructure
The existing infrastructure for distribution system is inadequate to provide minimum required drinking water This infrastructure is not able to carry existing 42 MLD supply – whereas city presently needs 88 MLD of supply. Due to uneven topography of city there are many low pressure points. Besides this, except RUIDP no major reorganization of distribution network has been carried out in last 3 decades. There are many tail ends. There is shortage of adequate storage facilities. The distribution network needs strengthening by construction of CWRs, ESRs, GLSR, feeder mains, rising mains and distribution networks.
4.6 Worn-out Pipelines
In old city there are decade’s old GI pipelines that have corroded and punctured resulting in inadequate flow. A major problem of scaling in old CI/GI lines resulting in low carrying capacities is also observed. Due to construction of roads, and plying of traffic, wherever distribution main lines have been laid frequency of leakage and breakages is heavy. Since, distribution main lines are exposed to rocky surroundings, though they are buried underground. The length of such lines is around 170 km and diameter of pipelines is 50mm to 350mm.

4.7 Uncovered Areas
Most of newly developed areas, and developing areas are deprived of piped water supply facilitates. On broad estimation this is about 30% of present populated area.

4.8 Power Transmission System
Major head works are not connected by electrical feeder mains that can ensure regular power supply during maintenance or breakdown in one of the power transmission lines. Even normal power cuts to city affects pumping from the head works.

4.9 Rejuvenation of Assets
Chemical storage facilities, Step-wells, pumping stations, office and residential complexes also need to be rejuvenated as they are in very poor state.

4.10 Lack of Communication Facilities
There is a lack of effective communication system between Jaisamand, Jamar Kotra, Kalrawas, Mansi-Wakal, and various sources. There is no proper system of production metering and distribution metering.

4.11 Commercialisation of water supply
Prior to 1987 the people of Udaipur used to pay Rs.14 per month and water service was available every day. Currently, the people of Udaipur get water connection on two conditions, (1) capacity to afford (2) legal entitlement as city dweller. The water distribution authority has fixed a flat price of Rs. 106 for two months for the city dwellers and Rs. 80 for the users of semi-urban areas. In doing so, the state has overlooked its basic service to its citizens, especially the pool sections of the people.

4.12 Equity Principle Is Neglected
As mentioned above, the state has emphasized service delivery on the principle of affordability. As a result the poor and marginalized sections of the society have been neglected in the service delivery process. In this connection, it is important to mention that the Constitution of India has emphasized that in the governance of the country the state should take the principle of social justice and equity into consideration.

5. Local Understanding about the Water Supply System
Despite the water problems in urban areas and the increasing demands for water supply in Udaipur, there has not been any common understanding about the problem and steps required to
address the problem. In this section, we have highlighted the ongoing understanding of local people about the water problem and ways to find a solution.

The rapid expansion of city of Udaipur has impact upon the rural areas which raises the issue of urban-rural sustainability. The rural–urban interface is characterised by a co-existence of urban and rural activities and institutions. It is increasingly recognised that linkages between the rural–urban areas is limited in spatial terms but also extends in terms of the commodity flows in this case the water resources. It is often seen as zone where particular (often conflicting) pathways for development are considered in evitable, yet the future course seems to be that urban space is expanding rather than diminishing. Changes are rapid with today’s landscape becoming tomorrow’s brown fields and housing estates for urban migrants. Amidst these changes conflict over water is intensifying. As a result, it is the rural populace whose dependence on small scale agriculture, common lands or conservation areas is coming under threat from urban expansion and ever increasing demands for the life sustaining resources like water.

The ambiguity of the rural-urban interface which is split between urban and rural jurisdictional boundaries, presents significant governance challenges. There are often contradictory or absent regulatory frameworks, contradictory technology arrangements which put water as a resource under threat. There is a haphazard mixture of planned and unplanned operations and a tendency to undermine and flout regulations. This is an environment with increasing levels of discrimination and access deficit and a decline in social capital which poses enormous challenges for the livelihoods of an increasing number of rural populace. The approach on part of the policy planners, the government, the city civil society and the political class which is rooted in urban areas is limited by lack of understanding about rural environment, the perception and priorities of rural populace. This kind of approach results in formulating decisions which are not equitable thereby heavily loaded against rural populace. These important gaps in understanding are a symptom and are reinforced by an almost lack of effective participatory process and transparency in urban planning (in this case governing the water resource).

With no clear jurisdiction, there emerges a situation of organized irresponsibility where powerful actors who are rooted in urban areas tend to benefit from lack of regulation and clarity in policy regarding water resources. By contrast rural populace whose livelihood is dependent upon water are stripped away of their rights.

Planning and management of the rural-urban interface or lack of it has implications for the sustainability of both urban core and rural hinterland which are at least as significant as sustainability issues. There are some powerful interest groups in urban core who see exploitation of the rural as a pathway to sustainability of the urban. This can be known by the fact that there is an attempt on part of certain sections of urban core who see transfers of natural resource (in this case water) as the only solution to the water crisis that they often face. But such short term solutions will have impact on the urban core in a magnified form sometime later. In this connection, it is important to understand clearly that water and its accessibility is key to all sectors of the urban and rural core. This is being reflected in their perceptions and the various positions they have taken in relation to water.
Transfer of water from rural to urban areas through dams has been accepted willingly/unwillingly as the panacea to meet the increasing water supply needs of the city. Arguments both in favour and against the construction of dams have been made. Those in support of dams include the political actors, administrators, government and the various line departments, market forces, residents of Udaipur city, media and NGOs. Dams have been looked upon as the immediate solution to their problem. Institutions such as the Jheel Samrakshan Samiti are strong advocates for bringing water from the Sabarmati basin into the lakes through projects such as Devas II, III and IV. Their views are echoed by a majority of the city’s population who believe that the waters of the Mansi and Wakal rivers that are otherwise going waste flowing into the neighbouring state of Gujarat are put to better use by being brought into the lakes of the city. A general view was expressed in some quarters that given the changing rainfall pattern, the fact that the waters from Mansi and Wakal rivers are already being harvested by the recently completed Mansi-Wakal Stage I project how much water would actually be available for transfer to the lakes of the city through Devas II and the proposed Devas III and IV. In the same vein it was also argued that basin transfers go against the law of nature and therefore cannot provide a long term solution to meet the needs of the city. This view though has little support. The strong backing for the basin transfer projects particularly the Devas schemes from the city’s political actors leaves little doubt as to where the city and all the actors within stand on the lakes and projects underway and in the pipeline to augment water supply to the lakes.

At this juncture, it also becomes interesting to note the various perspectives on the lake ecosystem in Udaipur. State agencies and other actors are also planning or are in the process of implementing additional measures to augment water supply to the main lakes and to reduce pollution in these, the lakes of Udaipur city have been included in the National Lake Conservation Plan (NLCP) funded by the Ministry of Environment and Forests, Government of India. The project has funding for activities aimed at the interception and diversion of sewage, desiltation and de-weeding of the lakes, storm-water management, improvement of the inflow channels, installation of ozonizer, treatment of the catchments, shoreline demarcation and protection including development of bathing areas, and other measures aimed at protection and enhancement of lake biodiversity.

There may be value in exploring if these measures alone can reinstate the former glory of the lakes without having to resort to large projects particularly Devas III and IV, as these may evoke a response similar to the Mansi-Wakal Stage I project where the rural communities affected by the project protested vigourously against the project. While the needs of the city cannot be ignored whether it be augmentation of water in the lakes or water for direct use by the city’s residents, given the continuously growing demand and natural limitations of basin transfers there is a need for residents, planners and activists working to protect the lakes to examine the feasibility of options such as recycling of water supplied through the water distribution system, revival of the wells and bavris (step-wells) where possible in the old city area, installation of roof water harvesting systems, recharging of groundwater aquifers and other similar measures to meet the city’s needs. These coupled with the measures being undertaken through the NLCP may in fact go a long way in keeping the lakes full and to a great extent meet the city’s requirement of water. Building support within the city’s residents for this perspective is a challenge and one for which a well thought-out strategy would have to be evolved.
Another factor that critically affects the Pichhola Lake in particular is the growth of the old city particularly the conversion of homes and other property into guesthouses and hotels. The government of Rajasthan in 1997 declared a ‘no construction’ zone around the lakes, and yet the growing tourist traffic continues to drive construction and conversion of property in the lake vicinity into hotels and guesthouses often flouting the ‘no construction’ notification.

While the flouting of construction norms cannot be excused, many of the hoteliers and guesthouse owners are locals who culturally relate to the lake, and appealing to their sense of ownership and relation to the lake together with enforcement of the construction norms could contribute in some way to better shoreline and lake protection. The efforts of the Lal Ghat Sangh, a group of local hoteliers and shop-keepers in the Lal Ghat area who regularly contribute some money and time for the upkeep of the area is noteworthy.

The challenge for such locality based initiatives probably lies in making membership to these more inclusive and broad-based. It is only appropriate to point out that access of the poor to the lakes must be safeguarded; if the lakes become the preserve of the tourists and relatively better-off residents alone, the poor for whom the lakes hold more than aesthetic and cultural value would be deprived of their claim to the lake and its waters. Efforts by the state and other agencies involved in lake conservation may meet with success only through the involvement of robust locality based institutions that comprise local residents including those who regularly bathe in the lakes, hoteliers/guesthouse owners, shopkeepers, and temple authorities.

The proposed lake conservation authority that is to be set up under the NLCP proposes to have a single institution for the Pichhola-Fatehsagar lake complex with a local level lake conservation committee aimed at conserving each water body. This is an attempt at bringing together all the players who are in some way or the other associated with the lakes, a much needed platform in the absence of which there has been considerable difficulty in managing the lakes and in their upkeep. Space must be created in the lake conservation authority or at least at the local level lake conservation committee for representatives from the locality based institutions mentioned above.

6. Need for Fresh Strategies

Since 1987 there has been an increasing demand of water supply from the people of Udaipur city, both due to large populations and large per capita use and waste by industrial units and others. Urban water supply sources for Udaipur city have been depleted, polluted or destroyed its sources of water like rivers, lakes and tanks and in many cases even groundwater. The rain water harvesting system has not been taken seriously. Lack of provision of adequate minimum water for vast proportions of poorer segments (especially slum areas) on the one hand and indiscrimination use of ground water by households, industries and commercial actors without paying any price on the other hand is typical picture of Udaipur city of Rajasthan. Thus having exhausted, mismanaged and polluted the local sources and after continuing to neglect the local water potential, the Udaipur city is increasingly look to get water from rural areas by proposing new dams to satisfy its water demands.

In the light of the observations, we argue for various options for augmenting water supply in Udaipur city, in addition to demand management, which the policy makers have ignored. In this
connection, we suggest that the policy makers and various stakeholders should draw lessons and experiences from other cities of India, especially from the cases of Chennai and Bangalore, where efforts are made to augment water supply through rainwater harvesting, groundwater recharge and wastewater recycling. Successful case of rainwater harvesting, especially in Chennai, supported with groundwater regulation Act has enabled in overall improvement of water resources in the city and through roof-top rainwater harvesting at household level. Though this is a novel effort of the Tamil Nadu Government, what is equally important is innovative measures promoted by private and individuals in Chennai City to augment water supply and in treating wastewater. Though the urban water supply and management in Chennai gives an idea about the importance of rainwater harvesting and regulating ground water extraction we also emphasis the need to augment water supply, through a decentralized approach.

Decentralised approach is the need of the hour where powers are devolved to local institutions and where co-ordination among the state, private sector and civil society are ensured for evolving water supply options in Udaipur city. For this, the State should decentralise the water sector to facilitate participation and inter-sectoral co-ordination, develop and operate water supply that is more responsive to the needs of the users and to take the social justice and equity principle into consideration. More importantly, effective regulations need to be placed for participatory institutions so that the institutions are sustainable. This calls for the government to provide an enabling environment by shifting away from centralised to decentralised governance system and creating a debate among users through a framework. Moreover, there is a need to look at the local options for water supply augmentation and proper management of available sources. If these options are properly taken into account, there is little justification for large dams as option for water supply of the city.

In addition to the above policy concerns we also emphasis on the following issues to deal with the problems revolving around the existing water supply system in Udaipur City. These include:

- Awareness among the city dwellers about the social, economic and environmental costs of such projects
- Proper planning and implementation of the R&R policy
- Consideration of social, environmental and economic costs on rural people.
- Appropriate cost benefit analysis
- Need to look at the alternative ways of augmenting water supply in the city
- Coordination among different departments at the local level
- Promotion and implementation of water conservation efforts and programs
  - Proposals that use internal water system judiciously
  - Need based supply should be advocated

7. Directions for Future Research/Project Work
- Strengthening the knowledge base for studying the Rural-Urban water transfers through dams and their rural/urban impacts.
- Follow up of construction and operation of Dewas II to highlight the consequences of the dam construction and their actual efficacy.
• When the group was working for ascertaining the ground water situation in the region it has come across various difficulties like collection of the primary data and as there was no prior work done on the subject so no data was available.

• Making the masses aware of the limited use of water to make and improve the ground water levels and to stop the region from converting towards a dark zone. So information drives must be conducted at the societal level through network with NGOs.

• Future research in the area of lake ecology and its impact on the social and economic systems of the area should continue to move out of the Pichhola lake area into both upstream tributaries and downstream fed rivers and lakes to gather a whole picture of the watershed. Specific research should focus on the conversion of small feeder lakes to land. The pressure for land area to develop for housing to feed the continued urban migration of the region fuels the conversion of lakes. Of 100 small lakes that used to feed the system, it is rumored only 55 still exist and that the others have been converted to land that is sold. One such lake area had stopped further development after construction began in the lake bed. The disappearance of these lakes has a crucial impact on the ecology of the water shed, the social system of the migrants, and the economic drivers that continue the migration and increase the demand for land.

• Another major case study that should be undertaken is on Udaisagar lake. All lakes in the lake ecosystem are interconnected therefore they all effect the ecosystem in which they exist. Udaisagar being the last lake in the chain of all the lakes is receiving all the contaminants and the pollution being flushed downstream. Industry has a strong impact on this lake, both in its pull of water out and its dumping of untreated industrial effluents directly in the lake. The bottom of the lake has become heavily silted, and pollution dumps are heavy. This use of the river and lake system by industry is inclusive up and down the system. Chemical industries are major contributors to the problems of Udaisagar and the Ahad River, while other areas are affected by the large marble industries in the area.

• Marble slurry discharge into the land releases chemicals that stay in the ground, flow into the lakes, and creates dust deposits after the water runs off that affect human health. Rajasthan was discovered as a mining opportunity for marble at the time of construction of the Taj Mahal. Over the last 25 years the industry is continuing to grow, and is an important economic contributor to the city, state and central government. The threat of the growth of industry is the slurry, which is an indestructible waste product. It is currently against the law to dispose of the slurry in the environment, but many industrialists ignore the High Court Petition and monitoring of the situation is nonexistent. Marble companies should be investigated as they relate to the work of Panchayats and UIT proposed regulations and monitoring. Ecologically sound reuses for the slurry should be investigated and proposed. A common suggestion is the inclusion of the slurry in concrete mixtures. Since much new construction in the area uses concrete as
basic structure, this may prove a successful way to recycle the waste product in a safe way.

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Case Study on Policy and Environmental Drivers of Access to Water

The City of Lakes and Its Water

Lakes in Udaipur

Udaipur, known as the City of Lakes, is nestled in a system of interconnected lakes that has sustained the city over the past few centuries. It is the historic capital of the former kingdom of Mewar in erstwhile Rajputana and lies in the Indian state of Rajasthan. The ‘man-made’ lakes of Pichola, Fateh Sagar, Udaig Sagar, and Swaroop Sagar, cradling the city, are considered some of the most beautiful lakes in the country. These were constructed between the 14th and 17th centuries by the then rulers of the area.

Pichola Lake is one of the oldest and largest in the state of Rajasthan. Built in 1362 and located in the heart of the city of Udaipur, Pichola has been a main source of water, spirituality, and recreation for the people of Udaipur for last few centuries. Historically, the lake was an integral part of the lives of the people living in the city. A major portion of the population of the city was physically located around Lake Pichola. A large number of temples, old houses, bathing and washing ghats are built around the perimeter of the lake. The lake played a very central role in the lives of people in the past.

Many temples have been built on and near these ghats. But a significant number of these temples have fallen into a state of disrepair or have been privatized. One hotel, which had previously been a temple, has altered the shoreline of the lake to suit its interior decoration. A large number of people bathe at the ghats and women wash their clothes along the lakefront. Most of these bathers and washers come from localities around the lake which receives piped water supply only two hours every two days. They have been coming here for many years and the lake has been part of their daily lives.

The population residing around the lakes has increased considerably and is from diverse class, caste, and religious backgrounds. Old homes built around the lakes are slowly and gradually being converted into guesthouses or hotels. This is happening because of the fast growth of the tourism industry in the city in past few years.

As the central image of the city of Udaipur, Lake Pichola has become the major attraction for domestic and international tourists. The view, beauty, and historic importance of the lake in the story of Rajasthan pull tourists to the city to experience the lakes. The tourist season spans from the month of November to the month of March each year. The total number of tourists that visit the city during this period is estimated to be equal to the population of the entire city, which is about half a million. Naturally, tourism is one of Udaipur’s largest industries. To earn their livelihoods, many families and communities rely on the tourists drawn to the city. These hoteliers, owners of guest-houses, shopkeepers, drivers, and people from many other professions

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2 The ‘ghats’ are masonry bunds built along the boundary of the lake with steps descending into the lake. This is to facilitate entry and use of the lake water from different purposes.
know the close connection between the lake—especially the water level in the lake and perceived quality of the lake water—with economic well-being their families.

**Bawadis: Another Old Source of Water**

Equally, crucial role has been and is being played by *bawadis*. A *bawadi* is a step-well structure built near one or more temples, in order to tap groundwater while simultaneously recharging the groundwater storage. The bawadi was a common, sacred source of water, serving water needs of a majority of people in the vicinity. This direct and very close relationship between the people and the source of water they utilized ensured that the structure of the well and the quality of water was maintained over centuries.

The bawadis of the Udaipur did not remain untouched during this transformation. For example, the Maaji-ki-Bawadi, which is the one of the big bawadis in the city, is located in the Chandpol area of the old city. It has an average depth of 15 to 17 feet. Built almost 200 years ago, it was primary used by affluent classes of the society, but was opened to all people after the severe drought of 1986. Today, it is said to be serving up to 1,00,000 people daily. The state government, through its agency, took up the responsibility of supplying water from the bawadi to the people from the surrounding three colonies by installing a pump (of 9 horsepower capacity) which runs for 6 hours a day. The priest of the temple of which bawadi is a part, claims ownership of the bawadi and supplies water to the PHED free of charge. The residents pay a flat rate for the water which is supplied for 2 hours every alternate day. They store the water by running motors which pump the water into storage tanks. Before consumption, the water is purified by covering the supply tap with a piece of cloth. A charge of Rs. 119 for residential consumers and Rs. 270 for commercial consumers is collected bimonthly.

**Piped Water system**

However, as the city and its population grew, the water from lakes and bawadis was not sufficient. As everywhere, the policy makers in Rajasthan felt that the growing needs of basic amenities for urban population would require intervention by the state, as it would require large capital investment. The Public Health Engineering Department (PHED) of the state government was created as an institution that will create and run public water distribution systems, supplying water through pipes and taps to the urban population. The primary mandate of PHED was to procure and distribute the water to end-users.

PHED came into Udaipur with the initiative of the then Chief Minister, Mr. M.L. Sukhadia to set up water supply system drawing water from the dam at Dewas. It was designed to meet not only water needs at that time but even future water need of the city of Udaipur. The construction of the Dewas system (named afterwards as Stage-I) started in 1969 and was completed in 1973.

Then came the drought years of 1986 to 1988. The age-old water supply system failed to perform during this drought. This led to construction of the water supply system accessing water from the Jaisamand lake through a pipeline. It involves pumping water up to the height of 300 metre and over the distance of 60 kilo-meters. The scheme, that was seen as an emergency measure for temporary relief, was completed in 1990 but continues to supply water to the city to this day.
Thus, the modern water supply schemes arrived in the city of Udaipur. The schemes carried with them their hallmark features: pumping of water from dams in rural areas, often up the gradient, and transferring it over long distances.

The piped water system in the city was gradually expanded further, but failed to keep pace with the increasing water demands of the city. The reasons are diverse. Most importantly, the existing infrastructure for distribution system is inadequate to provide minimum required water supply to the city. It is not able to carry the existing 42 MLD supply, whereas the city, at present, needs about 88 MLD of supply\(^3\). Most of newly developed areas and developing areas of the city are out of reach of the piped water system. As per a broad estimation, about 30% of the presently populated area is not covered by the pipe water system.

However, there are serious problems even in the existing piped system. First, the sources of water for the piped water system are grossly inadequate, even after commissioning of the new dam scheme of Manasi-Wakal project. The bore wells, which provide a portion of the water supplied to the city, also go dry during the summer season. There are many leakages and damages to the rusting pipelines that transmit water from distant sources to the city. Similarly, pumping machinery and electrical mechanisms at most installations are in the need of urgent rejuvenation. Efforts for rejuvenation of old filtration plants and improvement of disinfections facilities are not forthcoming.

Further, due to uneven topography of the city, there are many low pressure areas intermittently receiving low levels of water supply. Similarly, many areas at the tail ends of the main distribution lines continue to suffer badly. In the old city, decades-old pipelines have scaled, corroded, and punctured, resulting in low carrying capacities of the pipelines. Due to construction of roads and plying of heavy traffic, there is high level of frequency of leakage and breakages of the main distribution lines. The length of such lines is around 170 km and diameter of pipelines is 50mm to 350 mm.

No major effort has been undertaken to revamp or expand the existing distribution network in the last three decades. There is serious shortage of adequate storage facilities. The distribution network needs to be strengthened by construction of storage facilities, feeder mains, rising mains and distribution networks.

**Shift to Bore Wells**

Thus, the new pipeline-based water supply systems proved to be grossly inadequate due to the emerging water needs of the city. As industries expanded, tourism boomed, and population of the city exploded, the limited water supplied through pipe-connections (currently provided every other day for 2 hours) could not satisfy growing thirst of the city. This increased demand led to adoption of yet another technology by the privileged, viz., the bore wells. Bore-wells, dug with specialized rigging equipment, give access directly to underground aquifers which store water. People, who could afford to invest large sum of money dig bore wells to meet their personal water needs. With no policy or legal regulation or any control of any sort in place, these people extract groundwater in an unrestrained manner.

\(^3\) MLD = Million Liters per Day which is equal to *** Mcft (Million cubic Feet).
Pollution and Contamination of Water

But the pressure of increasing demand is not the only matter of worry for the water system in the City of Lakes. Equally important are the factors that affect the supply of the water from the different sources.

At many places in the lake, one can see an overgrowth of both water Hyacinth and the algae, indicating very high levels of pollution in the lakes. The pollutants from Pichola lake also impact the lake system as a whole, as water from the lake moves further into Fateh Sagar, Udai Sagar and eventually into the river system.

Pollution from the surrounding area is caused by many factors, but the most obvious are the pressure of fast increasing population and growth in the tourism and other businesses in the city. With almost doubling of the population in the five-month long tourist season, the unbearable pressure is exerted not only on the water supply system but also on the sewerage and garbage collection systems.

It is reported that, in the past, the old city had a system of collection of solid waste, which worked well. The efforts for establishing a modern sewerage as well as solid-waste management systems could not keep pace with the exploding population and booming business activity.

While there are dumpsters and trash collection sites around the city, many people do not use them in an appropriate manner. Often trash is tossed near the collection bins, instead of putting. The trash lying outside the bins is not collected when trucks come to pick it up. Stray dogs in the city also open these bags and rummage through for food. As a result, trash spills into the streets and storm drains and ultimately end up in the lake itself. While some waste is biodegradable, stray dogs and homeless cows eat most of this before it reaches the lake. Non-biodegradable water including plastics, dyes, and chemicals from the refuse further worsen the pollution levels in the lake.

It is reported by many citizens that the covered or underground sewerage lines are clogged and do not function for various reasons. Sewerage flows through open lines in the city, which were originally meant for storm water drainage. The municipal sewer lines run under the lake. Maintenance of these lines has been said to be low; as a result, the cracks and leaks at joints in these lines are said to be contaminating the lake water. New sewerage lines that were built as per the recommendations of NEERI in the area have construction defects which cause the back flow of dirty water during the monsoon season. Local people failed to receive any relief from these problems even after repeated complaints to the authorities. As a result, they broke most of the sewer lines that had been laid out and started emptying household sewage directly into the surface drains intended for storm water runoff. Since the storm water drains were constructed to drain rainwater directly into the Pichola lake, the slopes of these drains now allows this sewer to flow into the lake as well. Besides the faults in the sewerage systems, many homes do not have a connection to the sewage systems. They directly drain their sewage into the streets, drains, or directly into the lake. Open defecation and urination are also prevalent in street corners across the city and around the lakes at night.
There is a common conception that much of the sewage in the lake is contributed to the problem by the large hotels amongst residents of the area. But, the large hotels and owners of many of the smaller hotels and guest houses claim that they have maintained sewer connections, as they are aware of the impact that a sewer can have on the lakes, the life-line of their industry. Tourists they believe would never accept such conditions.

The menace of sewerage affects not only the lake. It also has contaminated the groundwater of the city, making it unfit for human use and spreading water borne disease to those who have no other source of water. Contamination of bawadis by sewerage and solid waste have rendered their water polluted and contaminated, making life difficult for poorer people of city who have no access to the piped system for water. In the Chandpole locality around the lake Pichola, most of the hand pumps in the area have been abandoned as a result of the contamination of the ground water, aggravating the water scarcity affecting the poorer population.

There is another dimension to the ecological deterioration of the lakes. The growing demands of Udaipur city have exerted pressure on the forest in the catchment areas causing degradation of vegetative cover and soil conditions on upstream side of the lakes. Moreover, urbanization in the catchments areas of the rivers has aggravated the problem further. During periods of heavy rains, these forests and soils are no longer able to slow down or absorb rainwater, heavily eroding top soil in the forests, which then is carried away with the rainwater. This has choked off smaller feeder channels and deposited large amounts of silt and sediment into the lakes themselves. Lake Pichola has been a victim of this sedimentation. Parts of the lake are shallower than previously, and, with evaporation after the rainy season, pieces of earth are evident. The most ominous indicator is presence of the water hyacinth. These plants feed off the rich nutrients of the top soil erosion to grow in the lakes.

The accumulation of pollutants and sediments in the lake are directly affecting the biodiversity of the lake ecosystem. One of the major concerns is the level of oxygen dissolved in the lake water. Increases in proportion of nitrates and phosphates in the lake water—coming from pollutants and sewage—is choking out oxygen. The presence of the water hyacinth plants is contributing to the same. While this does not appear as a critical issue like refuse dumping, decrease in oxygen in the lake water has greater impacts. Fish are dependent on oxygen levels. Without the fish, the weeds like water hyacinth are ultimately left unchecked. Fishing—commercial, subsistence, or recreational—is now part of the history of the lake. This has affected the livelihoods linkages of the residents from surrounding areas with the lake. It has also eliminated the possibility of recreational fishing activity for tourist. The oxygen in the water also helps cleaning of water, on its own, by combining with different chemicals to create benign compounds, reducing the pollution of the lake. The inflow of pollutants has crowded out this natural cleaning process.

**Impact on Groundwater**

Although the adoption of bore wells is a technology used in many parts of the world, the adequacy of the aquifers under Udaipur city is a major concern. Udaipur is located in the Ahar River basin surrounded by the Aravali Hills. The aquifers in this area are said to have limited potential for holding water. Further, although these aquifers could be large, the amount of water that can be extracted from them is limited. Once water is extracted for these aquifers, the possibility of their recharge is limited and possible only over a long period. In short, the specific
geo-morphological characteristics of Udaipur’s aquifers put the city at great risk of ground water depletion.

This is not hypothetical anymore. A few years ago, residents of Priyadarsani Nagar, located on the outskirts of Udaipur, were able to easily access groundwater by digging bore wells to the depth of 150 feet. However, at the same location, residents now have to dig bore wells to the depth of 600 to 800 feet in order to access water. Despite drilling deeper, many residents are not ‘hitting’ water.

It needs to be noted that, apart from the residents, the ground water is also extracted in big way by other actors. The hotels and guest-houses heavily rely on ground water especially during the tourist season. The city also has significant concentration of industries involved in cutting and polishing marble stone, which consumes significant amount of water. Most of the marble industry units are dependent on groundwater. They have their own bore-wells or bring water from bore wells on the fringe of the city.

Thus, city’s growing population and the booming industries have caused the rate of ground water extraction to skyrocket. With no effective regulation on digging of bore-wells or extraction of groundwater, there is no reliable estimate of how much water is extracted and by whom. The grave fact remains that the levels of groundwater are depleting at an alarming rate. Thus, with an incredibly high extraction rate, it is undeniable that, without strict and effective regulation, the Udaipur aquifers will soon run dry.

In addition to the threat of Apart from near-permanent depletion of water, quality of the ground water is an equally grave issue. The characteristics of Udaipur’s aquifers have led to high concentration of many heavy metals such as nickel and zinc in the groundwater, causing many gastrointestinal diseases including stomach and ovarian cancer. Apart from the characteristics of the aquifers contributing to poor water quality, improper sewage disposal, over and misuse of agrarian fertilizers and pesticides, and inappropriate industrial dumping are also responsible for contamination of groundwater. Although some people are able to have access to and afford filtered municipality water, contamination in the groundwater have dire health implications for poor population of the city.

Dams: The Final Answer?

In this situation, the city appears to be beleaguered by a series of problems in securing adequate, reliable, safe, and sustainable water supply. These include: (a) polluted and contaminated lakes and bawadis, (b) piped water system with inadequate capacity and other serious problems, (c) depleting availability and unacceptable quality of ground water from bore-wells. In this situation, most policy makers and other stakeholders seem to be suggesting building of new dams in the rural areas as the effective and efficient solution.

However, this solution is not entirely new. As mentioned before, the city has been receiving water from the Dewas Stage I and Jaisamand dams. Dewas I dam supplies 122 Mcft of water to
Pichola lake annually, which is less than the 167 Mcft of water that was anticipated according to the original proposal⁴.

About 21.32 mld of water started flowing in the city from the Jaisamand dam from 1995. As the Jaisamand dam is situated about 338 metres below the level of Udaipur, water has to be lifted. The project requires 27.8 lakh of units of electricity per year for lifting water through pumps⁵. Diversion of water from the Jaisamand Lake is said to have led to loss of water for irrigation in about hundred villages. Further, the dam was supposed to be only a temporary solution to be used until the Mansi-Wakal or Dewas Stage-II was completed, this, however, has not been the case.

The drought of 1986-87 led to a greater focus on drawing water from the rural areas around Udaipur City. The Mansi-Wakal Dam was proposed in 1989. It was argued that, since the total water available after construction of Dewas II, III, and IV dam projects would not be sufficient to meet the projected demands of the city, another project was essential. As a solution, Manasi-Wakal Stages I and II schemes were proposed. Although the foundation stone was laid in 1989, the construction of Wakal Stage I was completed only in 2007. The dam is constructed on the river Mansi near village Gorana at a distance of around 60 kilometers from Udaipur city. Water from Gorana dam is transported to Nandeshwar tank through a pipes and a tunnel and then into Udaipur’s water supply system. The cost of the project was shared by the Government of Rajasthan and Hindustan Zinc in 70:30 ratios. In return, Hindustan Zinc would get 30% of water from the project.

Dewas Stage II dam is supposed to provide water for both the Zinc Smelter Plant at Udaipur and the city of Udaipur. Though it is still under construction, demands and preparations have started for Dewas stage III and IV dam projects.

Thus, the popular solution for resolution of city’s water problem seems to be constructing all these dams and help the beleaguered city. The question is whether this solution is really the best solution available. It seems to be favored and beneficial for the city-dwellers, but what are the costs involved and, most importantly, who would bear the costs of dams?

The residents of the city of Udaipur seem to believe that dams are the best solution to augment the water supply of the city and to provide for the drinking and livelihood needs of city residents. Furthermore, many of these stakeholders argued that the dams were beneficial to the tourism industry and hence to the economy of the city, as they would supply water to maintain water level in the lakes even during summer season.

However, this perspective often fails to incorporate the fact that, in many instances across the world, the dams proved to be expensive to construct. It is also common experience that the stakeholders who propose the dams often underestimate their cost and overestimate the amount of water that will be supplied.

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⁴ MCft is million cubic feet of water.
⁵ Singh Sunita (2002). Water Management in Rural and Urban Areas, 177, 179.
In contrast to urban residents, discussions with residents from rural areas near the dam site of Wakal dam revealed that their perspective is quite different. They felt that dam construction negatively impacted their livelihoods. First of all, the dam project diverted water away from their area to the city and reduce availability of water in local rural residents. In addition, dam projects led to displacement of village people. For example, construction of Manasi Wakal Dam reported to have caused submergence of 4022 ha of land and, thus, have severely affected livelihoods of nearly 6800 people (or 850 households) from about 8 villages.

Displacement has also been shown to contribute to a number of social and psychological stresses. In the displacement process, individuals are often separated from their extended kin and social support networks. Furthermore, in moving to new lands, conflicts arise between displaced people and the original inhabitants of these lands, if both groups compete for the same jobs and other resources. Dam construction has been shown to lead to a number of negative environmental consequences. The diversion of the natural flow of water caused by dams has been shown to contribute to deforestation, loss of surrounding wetlands, as well as the disturbance of fish migratory patterns. This negatively impacts the ecological balance of the area. Furthermore, dam construction can alter water quality.

As reported, no studies have been conducted to investigate the economic, social, or ecological impacts of dams in the Udaipur area. Most importantly, the rural people who would be impacted by the dam were not consulted when plans for the Mansi-Wakal project were drafted. Government officials only informed these individuals after the plans had been approved. In order to inform these individuals, these officials posted a notice at one location in the village instead of notifying each village member who would be affected by the project. This approach did not take into consideration the fact that many village people are illiterate.

In short, the construction of past dams as well as the construction of Manasi-Wakal has proved to result in a number of negative social and environmental impacts for individuals living in rural areas. These impacts should be taken into consideration in cost-benefit analyses that are performed when new dams are proposed for the city of Udaipur.

Thus, the question is, in the light of these impacts of the dams, whether dams should be considered as the most appropriate solution for ensuring reliable and adequate supply to the city of Udaipur. Or whether the city should consider avoiding this solution—to the extent possible—which disproportionately burdens the rural people, affecting their ecology, resources, and livelihoods? Whether it is possible for the residents of the city to mend their ways and rejuvenate lakes and bawadis by taking due care of their solid waste and sewage? Whether they could use the groundwater resources they have in judicious manner? Whether they could also supplement their water supply through measures such as rain water harvesting, water recycling, and water conservation? If this is the right path, what measures should be taken to convince the city people to take this correct path? Would they be convinced of the need to consider the impact on invisible, silent, poor, less influential, and politically weak rural people? Whether the legal penalties or awareness campaigns would be adequate to make the politically and economically resourceful city people to take these hard measures? The people of city of Udaipur and the people from the rural surrounding areas will have to find answers to these questions.
Lake to Puddle: A System Dynamics Approach to Social, Economic,
and Environmental Consequences of Water Use in Udaipur, India

Abstract

Water scarcity could define the modern era, as 67% of the world will experience water shortages by 2025. In Udaipur, India, shortages are already evident as lakes in the city dry to mere puddles every summer. The shortage in Udaipur results from the convergence of social, economic, and environmental factors and is especially detrimental due to the economic importance of lake tourism for city residents. Students from Washington University in St. Louis, in collaboration with the India Institute of Technology, Tata Institute of Social Sciences, and the Foundation for Ecological Security conducted a field study to investigate these shortages in greater depth. A system dynamics model was constructed in order to best examine: (1) interdependency of domestic, industrial, and tourist water use on the supply of Udaipur’s water sources; (2) areas for policy and conservation interventions to alleviate water shortages, and (3) areas of future research. While the availability of data limited the model that could be constructed, it allowed the authors to capture the interrelated factors influencing Udaipur’s water supply. The collection of additional data will help to test suggested interventions, which include reducing distribution losses, reducing water demand, and treating polluted water sources.

Keywords: water scarcity, system dynamics, lake tourism, Udaipur, India

Background

According to the World Watch Institute, “Water Scarcity may be the most underappreciated global environmental challenge of our time” (Barlow 2007, 3) which is making water “the oil of the 21st century” (Running Dry 2008). As early as 2025, it is estimated that 67% of the world’s population will face water scarcity (Barlow 2007, 1) and the worldwide per capita water supply will decrease by one third before 2050 (World Water Assessment Programme 2009). This will cause 7 billion people in 60 countries to experience severe water shortages. These shortages will not only affect the ability of individuals and industries to meet their daily water needs, but are also projected to increase food shortages, the number of armed conflicts, and the occurrence of waterborne diseases (World Water Assessment Programme 2009).

The convergence of social, economic, and ecological factors is causing global water shortages. These factors include population growth, urbanization, changes in consumption patterns, industrialization and economic development, reduced rainfall, and increased water pollution. Developing countries such as India are disproportionately affected by these changes, due to their dry climates, and underdeveloped water infrastructure (World Water Assessment Programme 2009).
Abstract: Access to water is a growing issue worldwide. These problems are often compounded in rural communities with limited infrastructure and governance or in arid or semi-arid regions where water is a scarce resource. This Winter Institute group examined the inequalities in water access that exist in a specific rural watershed in a semi-arid agricultural region of Udaipur, India, which is reliant on an irrigation dam for water resources. The group also explored issues of the commons and examination of the existing governance mechanisms in place to control allocation. Participatory Rural Appraisal techniques were utilized to engage the different communities within the watershed, which included focus group discussions, community mapping, and household surveys. Land and irrigation records were consulted as well as local water policy. The findings suggest that many factors influenced access, including power and social status, lack of coordination amongst organizations, difficulties with policy implementation. Spatial issues related to physical location within the watershed played a major role and often intersected with social structures to determine access. However, ultimately, climate and environmental uncertainties and lack of sufficient rainfall made the dam and canal system unreliable forcing overuse of groundwater resources.
MAGEEP Project Report

Investigators:
Lan Yang, Ph.D, Assistant Professor of Electrical and Systems Engineering, Washington University, yang@ese.wustl.edu
Da-Ren Chen, Ph.D, Associate Professor of Energy, Environmental & Chemical Engineering, Washington University, chen@wustl.edu
Yunfeng Xiao, Ph.D, Full Professor of Physics, Peking University, yfxiao@pku.edu.cn

Title:
An on-chip platform for ultra-high sensitivity detection of pollutants in air and water using whispering-gallery-mode optical microcavities

Project Objectives:
Characterization of the properties of single nano-particles will have tremendous impact in many areas, such as biomedical application, pharmaceutical testing, environmental engineering and single photon source for quantum information and communication. We propose to develop a chip-scale microscopic tool that approximates the size of eukaryotic cells for in-situ investigation of single nano-particles and use the tool to approach important environmental and biomedical problems. The basis for the technology is that physical associations and interactions of a nano-particle on an ultra-high-quality photonic resonator’s surface alters highly confined electromagnetic field and the residence time of photons in a way that can be measured and quantified. Our work will include fabrication of ultra-high-quality, photonic resonator on silicon chips, evaluation of the photonic resonator, theoretical modeling of single nanoparticle-resonator interaction system, demonstration of single nano-particle detection and monitoring using the resonator, and investigation of single nano-particle study for pollutants in air and water. The ultra-high-quality and photonic resonator has the potential to revolutionize and replace conventional tools to characterize properties and in-situ behaviors of single nano-particles.

Summary of Research Findings:
We have demonstrated mode splitting arising from the interaction of single nanoparticles with the highly confined electromagnetic field in an ultra-high quality WGM toroid resonator on a silicon chip. Light is coupled in and out of the resonator by a tapered optic fiber as shown in Figure 1a and 1b. The evanescent field extending from the resonator impinges a small distance (~100 nm) into the surroundings to probe targets captured onto the surface of the device. As more nanoparticles bind to the surface of the optic resonator mode splitting varies in discrete steps. Thus, binding event of individual nanoparticles onto the surface of the resonator can be counted in real time from the steps detected in mode splitting of the resonance frequency (Figure 1c). This observation suggests that the rate of binding events can be counted, which would therefore report the concentration of sensing targets. Figure 1d shows size measurement of standard polystyrene (PS) particles (Thermo Scientific, 3000 series, radius 30-175 nm) using the mode-splitting technique, which is good agreement with the actual particle sizes. As a proof-of-concept experiment to validate the effectiveness of using the novel mode-splitting technique for actual environmental sensing application, a hygroscopicity measurement on potassium chloride (KCl) is demonstrated in figure 1e, which reveals similar hygroscopic behaviors of KCl to those reported by others using bulk and expensive measurement instrument. The preliminary results are promising and provide encouraging endorsement for us to employ mode-splitting
mechanism in the ultra-high-Q optical microtoroid to conduct real-time, in-situ sensing through nanoparticles detection and characterization.

Figure 1. Single nanoparticle detection using mode-splitting technique. a. Schematic (left) and micrograph (right) of a fiber taper coupled ultra-high-Q toroid resonator on a silicon wafer. Inset: field distribution of the whispering-gallery mode. b. Green light shows the confined light field in the resonator. b. Mode splitting in real time upon deposition of nanoparticles onto the surface of a resonator. d. Measured polystyrene (PS) particle size through mode-splitting technique versus the actual size of the particles. Inset: scanning electron microscope image of a single nanoparticle (arrow) deposited onto the ring of the resonator. e. Measured KCl particle sizes as a function of relative humidity of the local environment.


Papers:

Invited Talks:

• “On-chip optical resonators for single nanoparticle detection and measurement,” “Bio-Optics: Design and Application (BODA)”, which is a part of “Optics in the Life Sciences: OSA Optics and Photonics Congress”, Monterey, CA, April 4-6, 2011 (Invited)

Invited book chapter:

• A bio-photonics chapter to a review volume entitled “Understanding Biophotonics: Fundamentals, Advances and Applications” to be published by Pan Stanford Publishing.

Patents:


b. External funding resulting from the MAGEEP funding

• NSF CAREER Award: Real-time Detection, Monitoring and Characterization of Single Nanoparticle/Bioaerosol Using On-Chip Resonators
  Amounts: $400,000; Time periods of the award: 04/01/2010-03/31/2015
MAGEEP Student Network

The MAGEEP Student Network was formed at the 2\textsuperscript{nd} International MAGEEP Symposium, December, 2008, in Hong Kong. The goal of the Network is to support research, enhance education and build friendships among students at partner universities through global collaboration. The Network connects 800+ students at 14 of the partner universities: Unicamp, China Agricultural University, The University of Hong Kong (HKU), IIT Bombay, Tsinghua University, Chulalongkorn University, Chinese University of Hong Kong, Korea University, Tsinghua, Peking University, National University of Singapore, Seoul National, Yonsei, and Washington University.

The MAGEEP Student Network has developed through a social media site built on top of the Ning platform (http://mageepdocnetworkning.com/). The website supports sub-groups of students with related research interest or schools. It also supports forums for a variety of discussions and commenting on most content added. Resources such as pictures, videos and papers are shared through directly uploading files to the site or embedding feeds from sites like flickr and YouTube. Finally, the site can be used for event publicity at partner schools.

Using the Network site, groups have formed for around research areas such as aerosols, air quality and water quality. One task that the research groups have taken on is collaboratively collecting papers in a variety of research areas using CiteULike (http://www.citeulike.org/). The personal benefit of CiteULike is that it allows students to keep track of the papers they are reading, uploading copies of the paper and tagging with a variety of tags related to the paper. CiteULike also extracts automatically the bibliographic information needed for bibliographies. A MAGEEP Doctoral Network group was created on CiteULike. Students from the partners have joined this group and when they save a paper, they check “share with group” and the paper is automatically added to the MAGEEP pool. The group has collected 223 papers, mostly on water quality and air quality. These papers are then shared through an RSS Feed to the research group pages on the Ning site (see Water Quality).

The MAGEEP Student Network provides a place where students feel comfortable asking questions and reaching out to other students just based on the MAGEEP affiliation. One area that has sparked a lot of interest is exchanging advice on travelling to partner institutes. The EECE 401, Washington University, class skyped with an IIT-B student before their most recent trip to India. The IIT-B students also reached out on the Network site and provided advice about what to pack and where to eat when they were on campus. The forum feature has most recently allowed coordination on literature library and planning student activities for the third International MAGEEP Symposium.

Leading up to the 3\textsuperscript{rd} International MAGEEP Symposium, the MAGEEP Student Network hosted a student competition called “Green Your Campus”. The objective of
the competition was for students to submit three minutes or less videos with ideas about sustainable changes that their campus could make. The network then voted on the videos to identify the favorites. There were 28 ideas submitted from four of the partner schools. Submitted videos were then invited to present posters at the Symposium and an expert panel will judge them. The judges will award the winners $5000. The second and third place will receive $3000 and $2000.

The student competition is the introduction to four days of student activities that will enhance the Symposium plenary sessions and build the Student Network with face-to-face interaction. The Symposium student program will kick off with a party at the St. Louis City Museum. The Washington University Engineers Without Borders will showcase some of their gadgets, like the electrolycle, at this event. Competition videos will also be shown. Saturday, students will make their own biodiesel at lunch, with lunchtime speaker, Maud Essen of the St. Louis Renewable Energy Club. Sunday, students will wake up for an early morning session at 7am on international collaboration. This session will bring in virtual participants from India and China, using an Adobe Connect virtual meeting. Sunday's lunch will be an exciting collaborative session with the Washington University Olin Business School's Skandalaris Center and the undergraduate Student Sustainability Fund to put on an IdeaBounce. This IdeaBounce will challenge students randomly assigned to think and present ideas on how to spend the Student Sustainability Fund. Sunday evening the Student Network is hosting a movie night showing, The Fuel Film. Monday's lunchtime talk by Dr. Steve Jackson will highlight energy and environmental opportunities in Washington, D.C. The final MAGEEP Network Symposium session, “Coming Together to Reduce your Campus Carbon Footprint”, will be on ideas that reduce your campus carbon footprint. This session will highlight things Wash. U. is doing, but could be implemented at other partner schools.

In just 20 months the Student Network has gone from an idea to 800 members, fantastic ideas and tons of connections. It is an exciting time for the network. Please take this idea back to your school, join the network, reach out to other members and contribute content. For more information see the MAGEEP Student Network site: http://mageepdocnetworkning.com/ or e-mail, Erin Robinson (Emr1@wustl.edu).