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* **Corresponding author**.

aninditaroy.chowdhury@gdgu.org

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Design of Capillary Lift Irrigation Model for Hilly Terrain

Kiran Kumar Dangwal[1], Anindita Roy Chowdhury[1]*

1 GD Goenka University, Haryana, India

Abstract

Background: At present, irrigation in hills relies solely on conventional systems. However, hilly regions pose distinct challenges for irrigation due to their rough terrain and restricted access to conventional water sources. **Objectives:** To illustrate an irrigation model prototype for hilly regions based on the principle of capillary lift using nanoporous material. **Method:** The study designs a table-top experimental model for hill irrigation and analyzing its performance based on recorded experimental data of capillary transfer under various confinement condition alongside mathematical modelling to design an on-site irrigation model as well based on this technique. **Findings:** Experiments and mathematical analysis demonstrate this feasibility in hilly terrains. The developed mathematical scale model for on-site capillary lift irrigation is an outcome of discharge dynamics validated using a precision tabletop model for one-hectare cultivation in hilly terrain. **Novelty:** While prior applications of this technique have been limited to medical devices and potted plant watering, this study involving scale model extends its scope to large-scale irrigation in challenging landscapes. The findings confirm the potential to design a practical irrigation system for such areas, offering a pioneering and sustainable approach in this domain.

Keywords: Barometric Pressure; Capillary; Green Energy; Irrigation; Nanoporous

1 Introduction

In hilly regions, conventional irrigation methods are often impractical due to limited access to water. Kalandarov and team discussed theoretical and methodological foundations for the use of an automated control system for drip irrigation of crops using mathematical modelling and simulations. They integrated multiple techniques using differential equations to account for soil properties and irrigation parameters[(1)]. Jadav and Patil's work revealed high conveyance of existing lift irrigation schemes and also highlighted the inefficiencies in water use due to discrepancies between the designed and actual cropping patterns[(2)]. Lamichhane and co-workers carried out a comprehensive indicator-based framework study to examine five components and 15 indicators to quantify sustainability for different irrigation projects[(3)]. However, research on hilly area irrigation is limited, with existing methods lacking efficiency and cost-effectiveness.

Lifting water without any usage of electrical / conventional energy for irrigation in hilly areas poses a significant challenge. Barometric pressure and capillary-driven seepage techniques used in this model have been the key factors to lift water without any external energy. This ensures a continuous water supply for irrigation by tapping subsoil reserves without depleting surface resources, thus, promoting an essential self-sustaining system for hill irrigation. This self-sustaining design supports terrace farming and addresses problems like water scarcity, rainfall dependency and provides a green energy intensive irrigation which in turn provides a solution to mass migration from Himalayan border villages.

In one of author's earlier papers, capillary lift approach was stated as one among various other sustainable approaches for integrated model of hill irrigation [4]. In a separate paper, detailed review was done to endorse the significance of capillary lift in hill irrigation [5]. There is a significant research gap in harnessing barometric pressure-induced capillary rise for hill irrigation. This study explores this gap through experiments to build up a model to achieve energy-efficient scalable irrigation solution for hilly terrains utilizing capillary-driven ground seepage technique to transport subsoil water to the surface for sustainable irrigation.

2 Methodology

Water can rise vertically to an elevation of 34 feet (10 m) at Mean Sea Level (MSL) due to barometric pressure, prevalent everywhere on the earth surface, wherever the atmosphere exists. The phenomenon takes place due to intermolecular cohesion, adhesion and surface tension [6]. No external force of a motor or pump is required for this purpose.

2.1 Model to Implement Capillary Lift for Irrigation in Hills

All cultivable land in the hilly areas is cut into terraces of height 10 to 12 feet high to hold water on the terrace surface and also retain soil moisture; the step elevation depends on the slope of the mountain or hillside. PVC pipes need to be inserted up to a depth where subsoil water is available which is usually 30 feet below the ground. Inside every PVC pipe, bunched capillaries of nanoporous material are inserted. As the water table varies along the elevation, the process may be repeated in stages if the depth is beyond 30 feet.

Schematic figures are illustrated in Figure 1 to show the side view of terrace farming and the top view of the terraces with the capillary lift mechanism; the placement of the PVC pipes (carrying the bunched capillaries) in the ground is marked. The number of capillary pipes required will depend on the area to be cultivated.

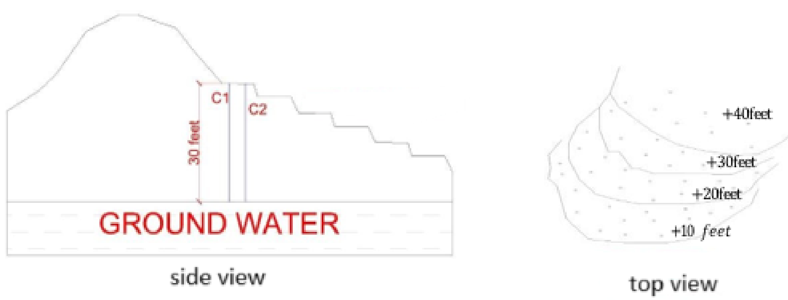

Fig 1. Terrace farming through capillary lift

2.2 Identification of capillary material under suitable conditions

Based on the actual ground parameters and possibilities, a prototype scale model was designed. To get the prototype, experiments were conducted, including an experiment to highlight the mathematical relation for capillary lift. One of the experiments was conducted to study the comparative performance of various nanoporous materials under confinement and identify appropriate capillary material under chosen conditions. Different capillary tubes were stuffed tightly with nanoporous materials like cotton, coir and paper towels. A comparative study of their performance was carried out. On the basis of their capillarity, cost and durability, appropriate capillary material can be selected. Further to it, another experiment was designed to select the appropriate confinement conditions for selected capillary material to minimize the time taken for water to reach the irrigation site.

2.3 Experimental Design for Tabletop Hill Irrigation Site Model

A capillary pipe of length 30 cm (1 foot) and diameter 1 cm stuffed with selected nanoporous material under chosen confinement condition, represents 30 feet on the ground. The lower end is kept in the wet source, assumed to be ground water and the upper end is left on dry sand to demonstrate the water lifted by capillary action.

Similar to the above setup, two more setups were taken. In this experiment, three groups of flowerpots (labelled A, B, and C) were positioned on stands of different heights (2 feet, 1.5 feet, and 1 foot, respectively) to represent terraces of a hilly area. Each set-up incorporated PVC tubes containing nanoporous materials, facilitating a comparative evaluation of water uptake for various elevations. This method offered a systematic framework to observe and measure the dynamics of water absorption across the different sets.

2.4 Mathematical modelling of capillary lift irrigation for hilly areas

Besides carrying out the tabletop experiment for on-site hill irrigation using capillary lift irrigation, a mathematical model was developed to forecast the necessary requirement for hill irrigation with the capillary lift mechanism. A land area of 1 hectare was considered to develop the mathematical model of hill irrigation based on this mechanism.

3 Results and Discussion

3.1 Analysis of Capillary Lift

Capillary lift was recorded through the capillary tubes of varying radii. Figure 2 reveals an exponential relationship between capillary rise and its radial dimension.

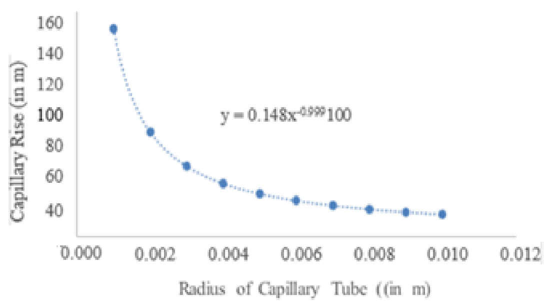

Fig 2. Capillary Rise Vs Radius of Capillary Tube

The exponential relationship between capillary rise and tube diameter (Figure 2) shows that small diameter changes greatly affect the height of capillary rise. Researchers observed that larger tube radii resulted in lower equilibrium heights and reduced velocities of capillary rise[7]. Capillarigation system for rice-based crops were studied in drought periods, thus, supporting the approach followed for hill irrigation[8]. The trend in figure 2 follows a power-law dynamics, indicating a non-linear correlation where minor variations cause significant effects. A 2021 reported review work with microchannels endorses this highly sensitive effect of dimensional change on capillary rise[9]. Experimental work done by Tian et al. in aeolian sand supports this result[10].

3.2 Selection of appropriate capillary material

An experiment was conducted to record the time taken for capillary rise for different types of capillary material inserted in capillary tubes to enhance the water uptake rate. Capillary materials included nanoporous materials ($\leq$100 nm), classified as microporous (0.2–2 nm), mesoporous (2–50 nm), and macroporous (50–100 nm). Materials like cotton and sponge, are widely used due to their high porosity, stability, and non-toxicity. The review work of Cai and coworkers explored fluid imbibition into fine pores driven by capillary pressure, detailing key factors influencing capillary rise[11]. Despite advancements, challenges in capillarity research persist, particularly in scaling from nanoscale to macroscale, where continuum models are unable to capture molecular interactions and the complex heterogeneity of porous media, making it a critical area for further study. In irrigation, cost, availability, and durability guide material selection, ensuring optimal capillary lift efficiency.

Primarily, considering the rate of capillary rise and durability as important parameters, cotton was identified as the chosen capillary material (Table 2). Cotton fibres function as a microscopic material with an intricate porous structure, where capillary

Table 1. Comparative performance of nanoporous material in capillary lift irrigation

S. No.	Material	Density (Kg/m^3)	Capillary spaces (nm)	Time taken to lift up to 1 foot i.e. 0.3 m (sec/min)	Cost per kg (INR)	Durability (months)
1	Paper towel	1201	Microporous 2-50 nm	131 seconds	3000	0.5
2	Cotton	448	Microporous up to 2 nm	145 seconds	120	6
3	Clay	1300	Mesoporous 2-50 nm	2.5 minutes	Free in nature	8
4	Sponge	961	Macroporous over 500 nm	Over 5 minutes	220	1
5	Coir	711	Macro porous over 100 nm	Over 10 minutes	80	2

action between fibrils facilitates liquid absorption and retention, resulting in high wickability and absorbency. Further to it, various confinement conditions were enforced on the chosen capillary material, cotton, and the time for capillary rise over a uniform height was recorded (Table 2, Figure 3).

Table 2. Capillary Transfer in Confined Spaces for Cotton

S. No.	Confinement condition of capillary material	Time taken for capillary transfer across 1 foot length
1.	Loosely kept without any confinement	3 minutes 30 seconds
2.	Tied with a thread	2 minutes 30 seconds
3.	Without binding, inside a narrow tube of 1 cm diameter	1 minute 45 seconds
4.	Thread tied capillary material pulled inside a tube of 1cm diameter with iron wire	1 minute 15 seconds

The result in Table 2 indicates the fourth confinement condition as the most appropriate condition for faster conduit.

3.3 Tabletop Hill Irrigation Site Model and Experiment

The selected capillary material (Table 1) and the chosen appropriate confinement condition (Table 2) were incorporated to complete the design of the tabletop hill irrigation site. Through this experiment, capillary behavior under diverse scenarios were explored. This exercise provided valuable insights to optimize irrigation strategies across hilly terrain.

In this experiment, the capillary hill irrigation mechanism was examined with PVC tubes of 1 cm diameter hosting confined cotton under thread confinement. Table 3 highlights the rate of capillary flow under chosen conditions to optimize water transport efficiency.

The experiments were conducted in prevailing conditions of hills with an ambient temperature of 18-24 degrees Celsius at an altitude of 7000 feet above mean sea level, using water available at that condition. Similar conditions prevail in the hilly region where cultivation employing this mechanism would be done.

Table 3. Record of Water Lift in Tabletop Irrigation Site Model

Set-up Number	Height of top pot (feet)	Time Duration for water to reach Higher Level Pot (seconds)	Rate of flow of water (foot/second)
A	2	190	0.011
B	1.5	120	0.013
C	1	50	0.020

From the observations recorded in Table 3, it can be further stated that the dry sand in each pot sequentially became wet, starting from C to A. Notably, the 1-foot-high pot (C) moistening in less than a minute, followed by the 1.5-feet-high pot (B) in 2 minutes, and the 2-feet-high pot (A) in over 3 minutes. Shortly afterward, water started trickling into the dry sand, and within a few more minutes, the sand in the upper pot of each set became uniformly wet, respectively. From the data record of Table 3, it

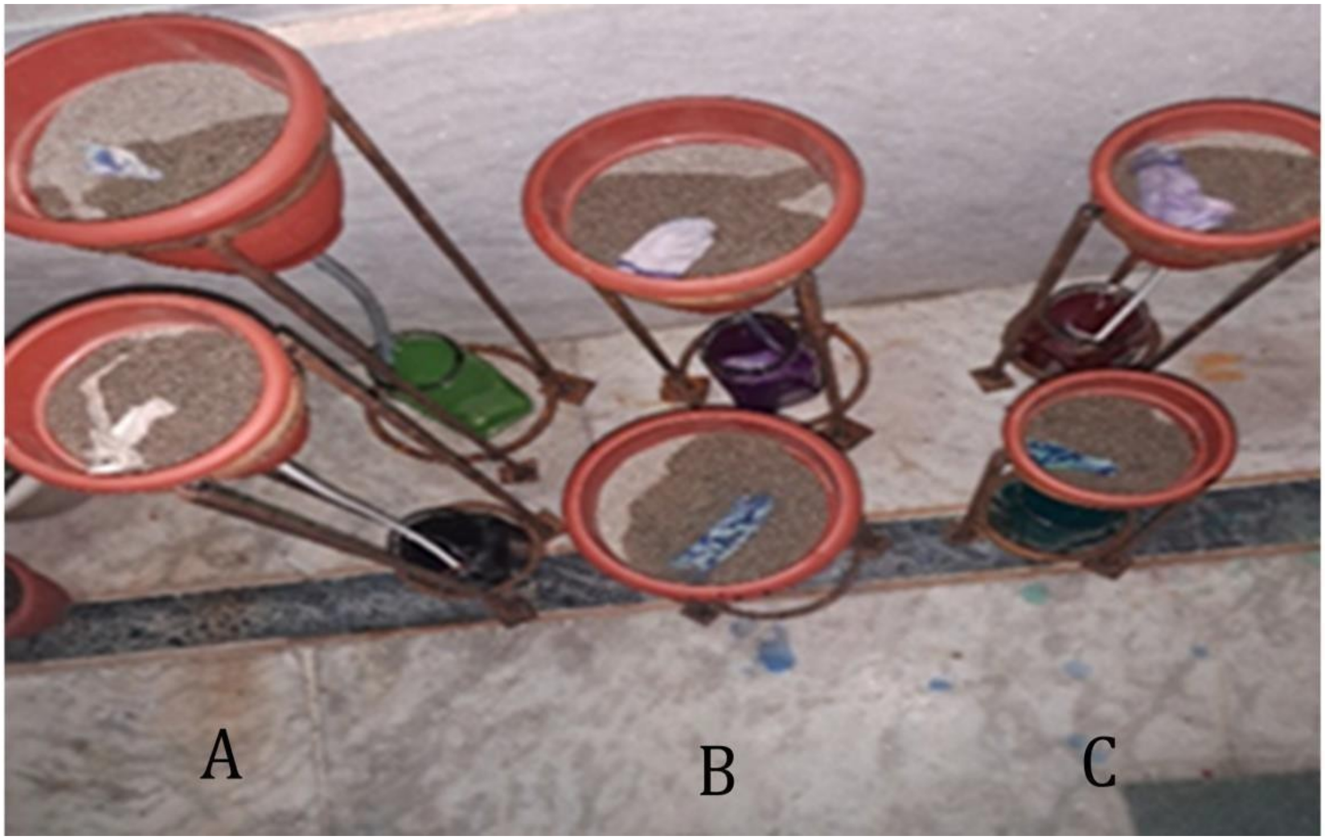

Fig 3. Experiment in progress

can be mentioned that the average rate of flow of water through the stated capillary material and confinement condition would be 0.015 foot/second, i.e. 0.44 cm/sec.

Applying a scaling approach, where one foot in the model corresponds to 30 feet on-site, allows for an estimation of water transport time in an actual irrigation setting. Considering a consistent flow rate, it is projected that groundwater from a 30-feet depth would reach the irrigation site in approximately 2,000 seconds, i.e. 33 minutes 20 seconds. This method provides valuable insights into water movement dynamics in real-world irrigation systems. In this technique, there is a crucial interplay of cumulative inflow and capillary rise variation due to complex pore-fluid interactions that can optimize irrigation practices. This finding is reinforced by the outcome of the study carried out by Zhang and team on capillary water absorption in sandstones in heritage sites [12]. Jalili and Zareabyaneh's study to assess capillary wick irrigation on greenhouse cucumber plant under different conditions, supports the approach followed in current study [13]. Work carried out by Chen and coworkers also showed the significance of capillary water as an intermediary for mulched drip irrigation to maintain the productivity of soil and optimize water usage in the saline-sodic sector of North-west China [14]. The work of Smagin and team showed that organic capillary barriers are capable of reducing unproductive water losses, thus, helping in biomass enhancement of the crop in dry regions suffering from water scarcity [15].

Through the above experiments, the authors could appropriately select a capillary material and confinement condition and apply the same to a real-time experimental set-up, a prototype to illustrate irrigation through capillary lift mechanism. This approach gives a lead to fill the gap existing in an optimized capillary irrigation design system.

3.4 Mathematical modelling of capillary lift irrigation for hilly areas

Based on the experimental record, additionally, a mathematical model for on-site capillary lift irrigation was developed, targeting one hectare cultivation area in hilly terrain. Utilizing a tabletop scale model, the discharge of a single capillary tube (30 cm length, 1 cm diameter) was estimated to be approximately 23.55 cm^3. Each PVC pipe was such that it contained 25 similar capillary tubes, making 588.75 cm^3 the discharge per pipe. Placing one pipe for every square foot area led to an estimated requirement of 255 pipes to effectively irrigate one hectare area. With the help of this model's framework, capillary configurations can be designed, thus, conforming adaptability to various crops and field sizes in hilly terrain. Some recent studies have highlighted effective performance of a system due to integration of mathematical modelling in irrigation design [16]. Significance of computer-aided design was also illustrated in the cost-effective hillside drip irrigation model proposed by Wang and co-workers [17]. Theoretical study carried out by Tawfeeq and team supports the fact that capillarity can be used as a green energy technique for irrigation [18].

Table 4. Mathematical modelling for Capillary Lift Hill Irrigation by Capillary Lift Mechanism

Parameters	**Value**
Area of land to be irrigated	1 hectare = 10000 m^2
Discharge of one capillary tube stuffed with cotton Capillary material = Volume of one capillary tube 30 cm (1 foot) long, diameter 1cm	23.55 cm^3
Number of capillary tubes in 1 PVC pipe	25
Volume of 25 capillary tubes = Discharge of 25 capillary tubes	588.75 cm^3
Area covered by 1 PVC pipe	1 square feet = 900 cm^2
Covered wetted area by 25 capillary tubes	25,500 cm^2 = 0.0255 m^2
Number of PVC pipes (with 25 capillary tubes in each) required to irrigate 1 hectare land area	255 pipes

Across hilly terrains, the height of the water table fluctuates. Under such scenario, autonomous operation of a capillary lift irrigation system leveraging sub-soil water offers a green solution and promotes the well-being of the local people.

4 Conclusion

This work presents a novel, energy-efficient capillary-driven seepage technique for sustainable irrigation in hilly areas facing challenges of water and power shortages. Suitable materials under optimum confinement conditions were identified through experiments for passive subsoil water transport, making it ideal for terrace farming without any requirement of external energy. A mathematically guided scale model demonstrated practical viability. Utilization of subsoil moisture decreases dependence on rainfall and energy-intensive irrigation. Slight modifications to this designed model depending on the specific region may be required for real-world adoption, enhancing long-term impact and offering a sustainable solution for Himalayan villages.

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