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Planning Post Carbon Cities

Editors:
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&
Joana Carla Soares Gonçalves

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Biomimicking Trees
Water Transportation in Buildings

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ABSTRACT: Nature inspires many products and designs around us. Trees, for instance, do not have pumps at their base, yet they effortlessly transport thousands of gallons of water across their height, daily. Mechanical pumps are the conventional mode of water transfer within buildings, but they have to rely on an external source of electricity for their output. Using fossilized carbon to generate electricity that carries water to great heights, has been the common practice. This paper explores the water transportation mechanism within trees, and through study of relevant bioinspired designs and experiments, critically reviews the possibility of proposing an alternate low-energy biomimetic water transportation system, for buildings. The research, through a process of extensive secondary data collection, 18small-scaled experiments, calculations, extrapolations, observations and analysis arrived at a 28point comparison between mechanical pumps and trees for vertical water transportation. A biomimetic water transportation system has been proposed by adapting 8 principles observed in trees that lend to the step-up modular system. Whereas trees exert 2.7 times more pumping power than conventional mechanical pumps to transport water along heights, they manage to achieve this naturally.
KEYWORDS: Biomimicry, Innovation, Water, Trees, Transpiration

1. INTRODUCTION

The world is experiencing water stress. By 2050, 75% of the world's population is anticipated to live in urban cities. Land being a finite resource, cities are becoming vertical, necessitating a vertical flow of infrastructure and resources. Facilitation of water at higher levels shall come at a higher carbon cost. In water-starved nations the energy dilemma serves as a double-edged sword, because the lack of water shall make energy expensive; and drawing water across great heights makes water expensive. Many rapidly growing cities in developing countries, are already facing problems related to water and energy.

Across the globe there are regions where reliable electricity is not available; remote regions unconnected with the grid; regions with ample ground water but no means to draw it out effectively.

This research seeks its inspiration from trees- the only living beings to carry water to such great height against the force of gravity. Nature is treated as a model, measure and mentor.[1] Biomimicry is applied as a design methodology to understand and emulate the anti-gravity, carbon neutral system of vertical water transportation observed in trees; and to propose a similar system in high-rise buildings.

2. LITERATURE REVIEW

The experimental research examined closely the functionality of trees, pumps, materiality, fluid mechanics and nature inspired designs.

2.1 Biomimicry

Biomimicry comes from the Greek word *bios*, life and *mimesis,* imitation. It is the conscious emulation of nature's genius.[2]
In this paper, nature (trees) influences design by observing Process and Function mimicry at the Behaviour level; since the research aims to study the water transportation process within a biological tree.[3,4]

2.2 Trees versus Pumps

2.2.1 Trees

The governing principle for water transportation in trees is transpiration. Trees require water for their various metabolic functions, one of which is preparing nutrients to fulfil the tree's energy requirements. Through photosynthesis the sun's energy converts carbon dioxide and water into glucose and oxygen.

Leaves, the primary source of photosynthesis, acquire CO_2 through stomata. However, every time the guard cells around the stoma open to accept CO2, water evaporates in the form of vapour. Only 2% of water absorbed via roots is used for the various activities of the plants.[5] Transpiration occurs during day time in the xylem vessels of a plant, which consists of hollow columns and tracheids made up of lignified mature dead cells, thereby, exerting no expenditure of metabolic energy. The loss of water due to evapo-transpiration develops a pressure deficit that pulls water up, from the root to the leaf

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petiole, in the fine xylem vessels under suction force. This upward movement of water in a tree is referred to Ascent of Sap and The Cohesion-Tension theory or Transpiration pull theory by Dixon and Jolly (1894). The theory relies heavily on capillary action within fine xylem vessels in the range of 0.01mm to 0.2mm; the strength of hydrogen bonds within water molecules (350 bars) that can overcome gravitational pull; the hydrophilic nature of lignin in xylem; the pressure differential created due to evapo-transpiration and the suction force created that pulls water higher up into the tree. [5,6]

2.2.2 Pumps

Pumps are mechanical devices that draw water across great heights. They usually employ a system of negative pressure (suction) to draw water at an inlet point and then discharge it from the outlet point using positive pressure displacement. Broadly speaking, suction pumps and positive displacement pumps work well under normal atmospheric conditions, though they harbour the limitation of pulling water to a maximum height of 10.34m theoretically, and approx. 7m in reality, considering partial vacuum conditions and frictional losses[7]. Suction pumps were studied in co-relation to off-grid solar powered water pumping systems – India's oldest application of solar power, since they are less energy intensive.[8]

2.2.3 Difference between Trees and Pumps

A study of trees reveals that, root pressure of 1 atm (14.7 psi) can push water to a height of 10-15ft.[5] By comparing this value with the pressure required by mechanical pumps: 0.433 psi for every feet of water rise; it appears that tree exert 2.7 times more pressure to effect water rise to a similar height as a pump.

Within a tree xylem, the absolute pressure of water is mostly negative, thus putting the sap under tension and making it thermodynamically metastable. While, mechanical pumps use electrical energy to transport water to higher levels; trees do it naturally by harvesting the sun's energy to create suction.

2.3 Water and Capillarity

Capillary action or wicking is the ability of a liquid to naturally flow in narrow spaces, even against gravity. The adhesive force between water molecules and lignified walls of xylem vessels, facilitate water's upward movement; while the cohesive forces between water molecules ensure the continuous column of water within the fine xylem conduits. Due to high surface tension, water can rise to appreciable heights. In a glass tube of 0.01mm bore, water will rise by capillarity to a height of 3m.[3] The height to which a water column will rise can be calculated by applying the Young Laplace equation. The equation proves that the smaller the tube radius, the higher the level to which a water column will rise.

Murray's Law, elaborates on the effectiveness of branching patterns. It proves that reducing the radius of the transporting veins within a leaf, results in increased pressure and flow of water.

However, Hagen-Poiseuille's Law states that the water flowing along pipes is proportional to the fourth power of radius, which means that a larger diameter shall result in more volumetric flow. Through an interconnected network of branching, a tree maximises flow of water and nutrients.

2.4 Design Approach and Applicability

Inspired by the metal fog harvesters of Chile, Vittori and Vogler's polypropylene mesh Warka Water Towers, and Stroock and Wheeler's hydrogel based palm sized synthetic tree[9], material suitability was studied by comparing various properties such as insolubility, porosity, surface tension, bore size, sorptivity, wettability, capillarity, permeability and strength, across different materials, such as lignin, hydrogels, organosilicate, polyster based wicking fabric, pyrex, copper, UPVS and polypropelene net.

It was observed that Polymers have good wettability; being hydrophilic in nature they assist capillary rise. Lignin is the most abundant polymer in nature and a product of agricultural waste.
Advancements in architecture and technology imply that our products need not be mined anymore, but can be harvested instead.

Figure 1: Branching Water Conduits on a Building Facade

3. METHODOLOGY

The experimental research, verified principles and formulae gathered during secondary data collection, by conducting 18 small scaled experiments (Fig. 2), and extrapolating the results on a 21m tall (7 storey high) building-scale application, to account for atmospheric pressure and propose a system diagram for a biomimetic water transportation system.

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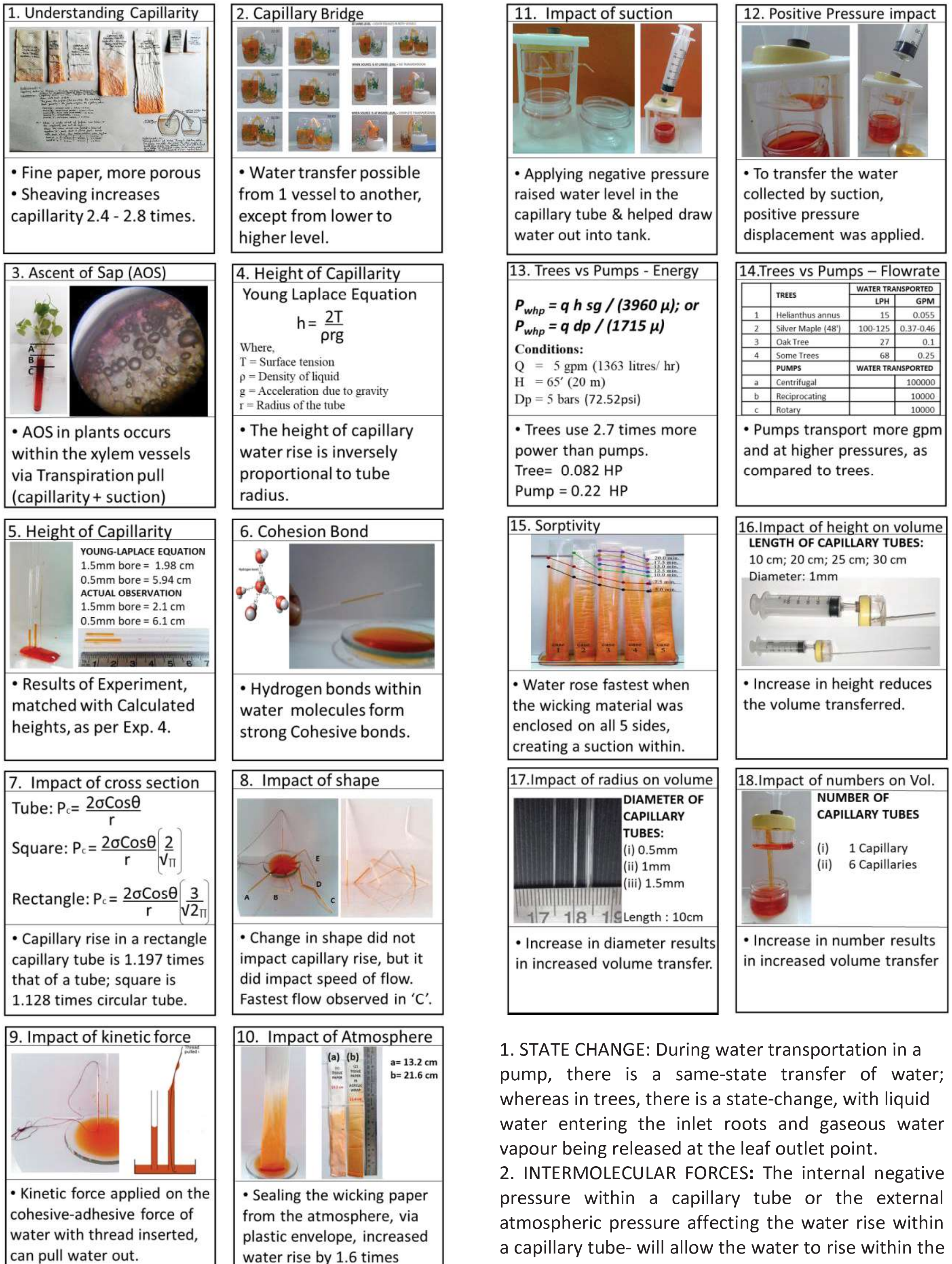

Figure 2: Experiments and Calculations Conducted

3.2 Data Analysis

It was realized that the major differences between the two systems were:

1. STATE CHANGE: During water transportation in a pump, there is a same-state transfer of water; whereas in trees, there is a state-change, with liquid water entering the inlet roots and gaseous water vapour being released at the leaf outlet point.
2. INTERMOLECULAR FORCES**:** The internal negative pressure within a capillary tube or the external atmospheric pressure affecting the water rise within a capillary tube- will allow the water to rise within the tube, but the same pressure will discourage the water from spilling or discharging out into another container, once it reaches the edge.
In small confined spaces, hydrogen bonds within water molecules, can overcome gravitational pull to form continuous threads of water.

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4. FINDINGS AND DISCUSSIONS

A point-wise comparison between how pumps and trees transport water across their height has been tabulated herewith (Table 1).

Table 1: Comparison between mechanical pumps and trees

COMPARISON BETWEEN MECHANICAL PUMPS AND TREES FOR VERTICAL WATER TRANSPORTATION			
S.N.	**PARAMETERS**	**MECHANICAL PUMPS**	**TREES**
1	**Flow rates**	Higher (10,000-1,00,000 gpm)	Lower (0.05 - 0.5 gpm)
2	**Volume of water transfer**	More (several million gallons p.d.)	Less (several hundred gallons p.d.)
3	**Pipe diameter**	Larger (50-125mm)	Small xylem vessels (0.01 -0.2mm)
4	**No. of conducting pipes**	One	Millions of inter-related network
5	**Energy Efficiency**	Better efficiency (0.082HP for 5gpm across 20m)	Lower efficiency (0.22HP for 5gpm across 20m)
6	**Duration of work**	Usually 1-2 hours in a day	Sunrise to sunset (8 hours average)
7	**Maintenance**	Periodical maintenance required	No maintenance
8	**Energy input**	Electricity required for pumping mechanism	Works on natural sunlight
9	**No. of parts**	Involves multiple mechanical parts- motor, impeller, vanes etc.	Involves mature lignified xylem vessels & leaf veins. Suction created due to evaporation from leaf mesophyll.
10	**Water lifting force**	Positive pressure and/ or negative pressure	Capillary action and negative pressure (suction)
11	**Water source**	Immersed in water source	Roots draw water from the soil through osmosis.
12	**Predominant force**	Mostly positive pressure displacement, for heights above 7-10m.	Mostly suction pressure exerted by D.P.D. Root pressure plays a very minor role in water transportation within trees.
13	**Energy Expended**	Pumping water involves 1% - 1.5% of all building energy	Transpiration of water allows the tree to generate energy for it's metabolic needs. $6 CO_2 + 6 H_2O = C_6H_{12}O_6 + 6 O_2$
14	**Water Output**	Constant	Varies with seasons and time of the day
15	**Impact of atmospheric conditions (Temperature; humidity; wind velocity)**	Un-affected by variations in atmospheric conditions.	Transpiration rates are influenced by changes in atmospheric conditions
16	**Climate Response**	Non-responsive; Independent to climate	Climate responsive
17	**Self healing properties**	Doesn't have the ability to grow or self-heal	As the girth increases, xylems mature at the centre of the wood & keep adding to the no. of water conduits. They constantly heal & repair.
18	**Cavitation**	Cavitation in a pump has to be mechanically removed.	Embolism within tree cells are taken care of by pits between xylem tracheids.
19	**Structural support**	The conducting pipe does not offer structural support to the building; and has to be braced along building wall along it's height.	Xylem vessels are lignified mature dead cells that offer structural strength to the tree; in addition to water transportation.
20	**Length of conducting pipe**	One single pipe to the top of the building	Branched network of many million smaller pipes (vessels).
21	**Force of Pressure**	Pipes subject to high water pressure and tension.	Controlled pressure within xylem vessels.
22	**Flooded state**	Water carrying pipes, are often empty when not in use.	The xylem vessels are filled with water at all times (even during night).
23	**State of Water**	Pumps carry liquid water from base to top and transfer liquid water to the OHT for storage. (Same State)	Trees carry liquid water from roots to the leaf, wherefrom water evaporates as vapour from the leaf mesophyll cells. This is referred to as the 'metastable state of water. (State Change)
24	**Pull vs Push**	A pump pushes water up (except in suction pumps)	A Tree pulls water up (except in guttation under root pressure).
25	**Factor responsible for carrying water higher**	Electricity fed motor is responsible for transporting water to greater heights by applying positive pressure.	Evapo-transpiration is the driving force for water transportation within trees, that works on suction.
26	**Physics behind anti-gravity water movement**	Pressure displacement	Cohesion-tension and Transpiration pull

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27	**Design constants**	The pipe diameter remains constant along it's length.	Xylem vessels, branche into smaller ones as they go higher and have complex venation patterns within leaves, to reduce pressure.
28	**Repair and maintenance**	If there is a crack within the pipe, or it breaks, the water flow is interrupted and the pipe leaks.	If a tree is injured (unless severed into half), the water route realigns itself within the xylem network to supply water in an uninterrupted flow.

Based on the data analysis and findings, it was apparent, that:

1. The capillary action experienced within the dead lignified xylem vessels can be replicated in fine bored capillary tube, to transfer water naturally, without applying external energy.
2. Transpiration pull within trees, relies on suction force created due to evaporation. Thus, if a suction were to be created in capillary tubes, it could successfully lift water higher up than the natural capillary level.
3. Water bonds within fine vessels are very strong and can overcome the gravitational force, to rise as one continuous water thread.
4. Atmospheric pressure and water tension within fine vessels will not allow water that has risen in a capillary tube to be discharged in same-state conditions, as observed in trees, necessitating an additional suction pull if water has to be used in liquid state.
5. Study of suction pumps, reveals that due to atmospheric conditions water cannot rise higher than 10.34m theoretically and about 7m in practice.

Based on the experiments and findings, a biomimetic water transportation system was proposed, that compared to the function observed in trees. (Table 2)

For the proposed biomimetic water transportation system, a few proposals were explored:

Of these, the stepped-up model combining transpiration pull (Capillary action + suction) was found to be most efficacious. Considering that suction pumps work effectively for a height of 6-7m, three cases were proposed for the stepped-up biomimetic system.

Case 1: Step-up every 3m.
Case 2: Step-up every 6m
Case 3: Step-up every 9m

Case-1 employs a capillary tube network system of 0.01mm diameter which ensures that the 3m water rise is natural and only a minimal suction is applied to

Table 2: Comparison between trees and proposed biomimetic water transportation system for buildings

BIOMIMICKING TREES FOR WATER TRANSPORTATION IN BUILDINGS			
S.N.	**DEFINING PARAMETERS**	**TREES**	**BIOMIMETIC SYSTEM**
1	**Hydraulic Physics**	A tree lifts water along its height, using Capillary Action & Suction Pressure (Transpiration	The tree-inspired biomimetic water transport system, raises water using Capillary Action & Suction
2	**State change**	A tree translocates liquid water along its height, but releases water vapour as transpiration.	Water for consumption has to be transported along the building height in same liquid state.
3	**Inter-molecular Forces**	Capillary action makes water rise in a fine bore xylem or tube, but it does not allow the liquid water to be transferred.	Water will rise using capillarity. For transfer, additional negative pressure shall be applied to overcome surface tension.
4	**Impact of numbers**	Trees contain millions of xylem vessels within their core that together raise several hundred gallons of water to the top, daily.	Increasing the no. of capillary tubes, increases the total volumetric flow, proportionately, while applying the same negative
5	**Modular system**	The xylem conducting vessels within a tree are a network of shorter vessels interlinked together, that traverse the whole length of the tree.	Dividing the total height of individual water conducting tubes into shorter segments - reduces the pressure exerted on the walls.
6	**Murray's Law of branching**	Branching patterns within trees reduce the pressure within & increase the flow of water. Thus the tree supplies water effectively to all its parts, expending less energy.	Reducing the pipe diameter increases water pressure within, and carries water effectively to greater heights.

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7	**Less Material More Design**	In nature materials are expensive, shape is cheap. Xylem conducts water, and also provides lignified structural support to the tree. The mature dead xylem vessels can withstand the tension exerted on them by the water column.	Creating a modular system, with interlinked shorter capillary tubes, eases the structural strain experienced by the conducting tubes, allowing for less material (thickness) to be used for their manufacture. The resulting system is strong and flexible.
8	**Solar powered system**	Evapo-transpiration from the leaf, triggers a pressure differential within, resulting in cohesion-tension pull under the impact of suction force, during day. Thus, sunlight triggers a continuous water movement.	In the absence of conventional pumping mechanism, solar energy is applied herewith for displacing the water out of capillary tubes, with the help of a solar powered suction pump.

'draw' water out from the capillary tube, and into a storage container, which then serves as an inlet source for the next batch of capillary tube network. As observed in Experiment 16, reducing the lift height results in more volume transfer; and also reduces pressure exerted on the pipe.

It may however be noted that to receive a volumetric flow equivalent to a 100mm dia. conventional pipe, 100 million capillary tubes of 0.01mm diameter shall be required. This system can be manufactured using hydrogel. However, the author suggests for this biomimetic water transportation system to be 3D bio-printed using lignin, from agricultural wastes, as a polymer-based ink. The fine tubes could be incorporated within the building skin as part of the wall or within hollow steel column.

Considering that medium height residential buildings utilize about 1% -1.5% of their total energy in pumping water, the savings appear modest, however, multiplied across several buildings the savings would be substantial. Even though this system is largely developed for off-grid regions bereft of electricity, the argument for energy-consumption within urban buildings is made to highlight that there is an energy and cost saving potential to this biomimetic system.

5. CONCLUSIONS

The research compared vertical water transportation mechanism in trees, with conventional mechanical water pumps: to propose a biomimetic solution that would be applicable on buildings.

The research study revealed that even though trees do not have electricity guzzling pumps at their base, they do have an internal pumping mechanism that is operated by solar energy. A close scrutiny of the water transporting members of the tree- the fine bored xylem vessels; the Cohesion-Tension within them and the Transpiration pull observed due to evapo-transpiration; was emulated within the proposed biomimetic system which gains its additional energy input from the sun, and mimics the water transportation function within a tree.

The proposed biomimetic system consists of capillary tube networks as water conduits and uses solar powered DC surface suction pumps, to draw water out of the capillaries. As a step-up modular system, it is replicable to a height of 21m.

This biomimetic system however, differs from a tree in one aspect- whereas water in a tree experiences state-change from the inlet to outlet stage, the proposed biomimetic system transports water in same liquid state.

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