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Water management lessons from nature for applications to buildings

Lidia Badarnah*

Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA, USA

Abstract

Water management and regulation in buildings have been facing real challenges with the increasing environmental awareness during the last decades. Current concerns of shortage in water resources increase the demands to enhance water management strategies. In this respect, buildings should be able to gain, conserve, transport, and lose water adequately. Efficient water management solutions can be extracted from strategies found in nature. Here, we classify a basic array of strategies for water management; discuss morphological features and active means; and list corresponding examples from nature, to facilitate the search for and the selection of strategies from the large database of nature, and inspire new design solutions.

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Keywords: biomimetics; architecture; buildings; rainwater-harvesting; moisture-harvesting; design; nature.

1. Introduction

Current concerns of shortage in water resources require alternative solutions for water management where buildings are able to gain, conserve, transport, and lose water efficiently. Rainwater harvesting and the reuse of grey-water in buildings have been investigated thoroughly in the last years, e.g. [1-10]. In the last few decades, various surfaces for water gain through condensation or concentration have been developed as coatings or applications on existing surfaces for a range of applications [11-13].

Alternative solutions for water management can be found in nature. Enormous management survival strategies where adapted through evolution. Many organisms employ morphological means to supplement physiological and

* Corresponding author.
E-mail address: lbk@mit.edu

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behavioral adaptation strategies, such as the special behavior and integument morphology of lizards [14]. Another example is the diverse structural morphologies evolved on plants' surfaces to influence wetting for optimal water management [15]. Emulating such strategies in nature for solving problems in buildings is known as biomimetics, which is an emerging field in architecture. One of the challenges in implementing biomimetics lies in the search for, and selection of, appropriate strategies from the large database of nature, as proposed by the BioGen methodology [16]. A recent work by Malik et. al [17] discussed surface features for survival in arid conditions that could inform new moisture-harvesting devices.

Biomimetic frameworks that analyze natural strategies for building applications are gaining more attention for various purposes [18-21], yet a framework for water management applications to buildings is lacking. In this paper, some water management strategies found in nature are presented, a framework that encapsulates these strategies is discussed, their functional morphologies and active means are distinguished, and the potential application to buildings is indicated.

2. Water management in nature

A literature review was carried out to source water management strategies found in nature. Special attention was given to organisms that live in deserts and employ unique strategies for adapting to extreme conditions, where they can obtain and conserve water, and prevent dehydration, among others. We find these organisms worth studying because of their extraordinary ability to manage water under water-scarce environments. This section classifies water management into four main functions: gain, transportation, conservation, and loss.

2.1. Water gain

Drinking is one of the obvious forms of water gain. However, this study explores other challenging water gain strategies such as surface condensation and uptake via surface diffusion, with a focus on regions with limited water resources.

2.1.1. Condensation

Fog represents an alternative source of water for some organisms inhabiting deserts. For example, the Namib desert beetle inhabits one of the harshest environments on earth, which experiences high winds, extreme temperatures during the day, and dense fog at dawn [22]. The Namib desert beetle is able to collect water from fog by fog-basking behavior [23], where water is collected on the elytra by condensation [24]. The Tenebrionid beetle digs trenches in the sand to catch water, which are constructed perpendicular to fog winds [25]. In some plants (such as cacti), the thin boundary layer of small leaves enhances water harvesting [26, 27]. Cacti's spines, besides reducing irradiation and transpiration rates, they increase condensation and channel the collected water down to the roots.

2.1.2. Diffusion

Some terrestrial organisms, including many amphibians, are able to absorb water vapor directly from the air via their skin. As an example, green tree frogs produce condensation on their skin by hopping from a chilly to a warm environment, and soak the dew generated on their body through their porous skin. The ventral side of the skin of the green tree frog has ridges and grooves, and the capillaries which are enclosed in the ridges allow absorption of water [28].

2.2. Water conservation

Water conservation is important when water is limited. Reducing evaporation rates and reducing radiation exposure are common means in some organisms for water conservation.

2.2.1. Reduction of evaporation rate

The existence of scales and waxy coating prevent evaporation from the skin [29], such as in reptiles and cacti (respectively). Little pores called *Stoma* (plural of *stomata*) open or close to control gas exchange and water loss in plants [30]. Many species have stoma partly covered by epidermal cells, which create a microclimate to protect the stoma from winds and atmospheric vapor pressure deficiency, and mitigates transpiration on hot and dry days [31]. Moreover, some plants such as Crassulacean Acid Metabolism (CAM) plants can control the opening of each stomata for lower transpiration rates [32]. CAM plants are organisms that pose physiological adaptation to extremely hot and dry environments, e.g. cacti, orchids, pineapple, and some ferns [33]. Nasal passages in many desert lizards and rodents decrease evaporation rates by cooling exhaled air and condensing water along the passageways [34].

2.2.2. Reduction of radiation exposure (irradiation)

Reducing radiation minimizes high heat loads and evaporation rates. Shiny reflective surfaces are found among organisms in deserts to reduce heat loads [35]. The presence of fur and hair on the skin results in reflecting a large amount of radiation [29]. Folding of leaves is another mechanism for reducing irradiation to prevent transpiration water loss [36]. Other desert plants have the property of shrinking their shoot while having the same surface area; in this case the surface is transformed from a concave to a convex shape [36], which provides an effective self-shading situation for the plant at extensive exposure to sun-radiation [37].

2.3. Water transportation

Water can be transported from one region to another at a large range of scales, with the force of gravity or via capillary action, especially in venation systems.

2.3.1. Gravity

Some organisms have special morphologies that exploit gravity and direct water to their roots; hence increase water gain, especially in arid regions, e.g. agave [38]. Agave is a succulent with a large rosette of thick fleshy leaves, where leaves end in a sharp point and have spiny edges. The concave shape of agave’s leaves directs rainfall or condensed water towards the roots. Ribs or grooves are another morphological adaptation for channeling the collected water to reach the roots, such as in barrel cactus.

2.3.2. Capillary action

Capillary action is the tendency of a liquid (e.g., water) to move counter to gravity in a narrow tube, or in porous material such as paper. It is observed to transport water in plants, where adhesion forces lift water to a certain height. Water transportation cannot occur only by capillary action, where *osmosis* (solute concentration difference) helps in lifting water to higher distances. Some desert lizards, such as the Thorny Devil, have a special integument that is able to transport water, even from the ground, and channel it to their mouth via capillary action [39, 40]. The integument consists of micro-channels of scale-hinges [40, 41], and a honeycomb-shaped micro-structure [42].

2.3.3. Venation

Venation is the distribution or arrangement of a system of veins. The pattern of venation networks in leaves responds to functions such as carbon intake and water use [43]. Leaf venation patterns which include a dense set of nested loops were observed to be an optimal transportation network even at events of damage [44]. Networks with hexagonal traits achieve high potential loops for a specific vein density and distance [43].

2.4. Water loss

Organisms lose water by three means [45]: cutaneous water loss (through skin), excretory water loss (through urine and feces), and respiratory water loss (during gas exchange). Water loss through skin (sweating) is one of the mechanisms for thermoregulation (latent heat transfer). The rate of evaporation increases with temperature and dry atmosphere.

2.4.1. Evaporation

Evaporation occurs through the skin that contains a complex vascular system and sweat glands, and includes two main layers: the epidermis and the dermis. The epidermis is the outermost layer of the skin, and the primary barrier to water diffusion [46]. The dermis is much thicker than the epidermis and contains vascular systems, sweat glands, and thermoregulatory nerves [47]. Increasing the secreted sweat to the skin surface is achieved both by increasing the number of contributing sweat glands and by increasing the amount of output of each active glands [48, 49]. Several internal and external physical factors influence the rate of evaporation in organisms [45], such as: vapor pressure difference, flow rate of air, temperature, surface area, and orientation.

3. Biomimetic framework

In biomimetics at least two domains are involved, where information from biology is transferred into engineering. In this process experts with different backgrounds apply different approaches, which require a unique framework to allow convergence between domains [21, 50]. The current framework distinguishes main functions for buildings and natural systems, identifies relevant processes and factors, analyses functional morphologies and means, and defines performance context, all together to be applied to a design solution for buildings, see Fig. 1. In this work, our focus is confined to the initial phase describing sources for inspiration and identifying potential applications.

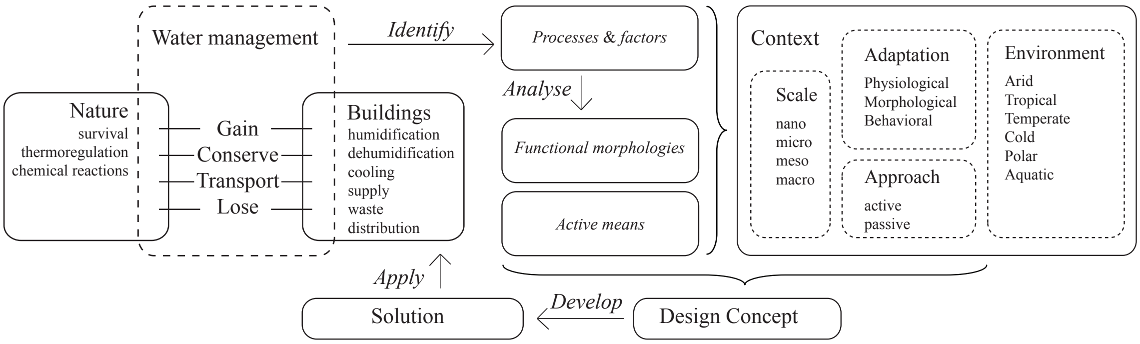

Fig. 1. Schematic representation of the biomimetic design framework for water management.

3.1. Function-based classification of processes and factors

The classification of the biophysical information introduced in section 2 is presented in Table 1. The approach of BioGen methodology is adapted for information representation, where four hierarchical levels categorize relevant biophysical data systematically [16]. On the first level the functional aspects are identified: water gain, conservation, transportation, and loss. Several processes are determined for each function. Numerous factors are determined to influence the processes of the functions. From the literature review, several representative organisms or natural systems for a particular adaptation strategy, referred to as *pinnacles*, have arisen to demonstrate such processes, which are summarized in the last level. Adaptation strategies could be abstracted either from an organism and/or a natural system (including animals, plants, nests, and ecosystems); they are addressed as pinnacles (literarily summits), resembling their importance and uniqueness. The content of Table 1 is a representative state for the current exploration, that can be extended and new data at various levels to be added in future elaborations.

Table 1. Systematic and abstract representation of literature review for water management.

Functions	Processes	Factors	Pinnacles
Gain	Diffusion	Porosity	Tree frog [28]
	Condensation	Morphology	Thorny devil [51]
			Rosette plants [26]
			Sand trenches [25]
			Spider silk [52]
			Namib beetle [24]
Conserve	Reduce irradiation	Orientation	Cacti [53]
		Reflection	Brittlebush [54]
		Folding	Leaves [55]
		Shrinking	Succulent [56]
	Reduce evaporation	Temperature	CAM plants [32]
			Kangaroo rat [34]
		Surface area to volume ratio	Cacti [57]
		Permeability	Lizards [58]
			Plants [59]
Transport	Gravity	Morphology	Namib beetle [60]
			Agave [38]
	Capillary action	Morphology	Thorny devil [40]
			Plants' roots [61]
			Venation networks [43]
Lose	Evaporation	Vapour pressure difference	Stoma [62]
		Flow rate of air	Poor-will [63, 64]
		Temperature	Human skin [49]
		Surface morphology	Elephant skin [65]

Table 2. Summary of functional morphologies and their potential application to buildings.

Process	Morphology	Pinnacle	Mechanism	Applications
Condensation	Hexagons	Thorny devil	Hexagonal structuring of integument surface decreases contact angle significantly and results in a super-hydrophilic surface [51]	Moisture harvesting
	Spikes	Rosette plant	The thin boundary layer of leaves improves water collection from fog [26]	
		Namib beetle	Hydrophilic elevated bumps on elytra attract water droplets from fog [60]	
	Knobs	Spider silk	Knots on silk fibers attract water from humid air [52]	
		Sand trenches	Constructing trenches perpendicular to winds attracts water droplets to sand particles from vapor [25]	
Transportation	Grooves	Namib desert grass	The presence of grooves on surface that run in the direction of the long axis towards the roots of the plant, provide a guided water collection and transportation, and reduced scattering of droplets [66]	Water distribution
	Capillaries	Thorny devil	The scales of the integument create micro-channels from a semi-tubular capillary system over body surface, which transport water to the mouth via capillary forces [40]	
	Venations	Leaves	A complex hierarchical network of nested loops in leaves (instead of linear) provides an optimal transportation even at events of damage [43, 44]	
Evaporation	Wrinkles	Elephant skin	Wrinkles provide sufficient surface area for holding moisture and evaporation [65]	Cooling
Diffusion	Pores	Tree frog skin	Little pores on skin surface allow direct diffusion of condensed water [28]	Humidification
Reflection	Trichomes	Silver ragwort	Trichomes are hairy structures that scatter light and result in reduced incident light at the interface [54]	Light shielding for water conservation

Table 3. Actions for water management and their potential application to buildings.

Process	Action	Pinnacle	Mechanism	Applications
Evaporation	Controlling permeability	Stoma	Open and close for gas exchange in response to osmotic pressure in the guard cells. The thick elastic inner walls and thin elastic outer walls of the guard cells, ensure an uneven expansion when inflated, thus result in the opening [31]	Humidity control
		CAM plants	Uptake of CO_2 mainly at night when temperatures are low and relative humidity is high, thus reducing evaporation rates [32, 67]	
	Vibration	Poor-will	Increasing evaporation rates by increasing airflow over moist vascular oral membranes by vibrations [63, 64, 68]	Cooling
Irradiation	Reorientation	Arizona Lupine	Paraheliotropic leaf movements result in lower leaf temperatures and decreased transpirational water loss [69]	Water conservation
	Folding	Leaves	During water stress, leaves roll and fold to reduce irradiation and keep stomata in microclimates with higher humidity preventing dehydration [55]	
	Shrinking	Succulent	The ribbed morphology allows swelling and shrinking, which creates self-shaded regions thus reducing irradiation [56]	

3.2. Functional morphologies

Many organisms exploit morphological means to supplement physiological and behavioral strategies for water management, which often function simultaneously with other challenges like thermoregulation [70]. Several morphologies are distinguished to promote water management via: condensation, transportation, evaporation, diffusion, and radiation reflection, see Table 2. These morphologies can influence surface functionality, among others, by decreasing or increasing contact angle for hydrophilicity or hydrophobicity (respectively), creating thin boundary layers for better water attraction, providing paths to direct water, or/and moving water around. The underlying mechanisms of the morphologies and their potential applications to buildings are presented in Table 2.

3.3. Active means

At challenging environmental conditions, some organisms involve active means to control evaporation and minimize irradiation for better water management, see Table 3. These actions, can control gas exchange processes at favored environmental conditions for minimized evaporation rates, increase airflow actively for enhanced evaporation, or change form for avoiding excess solar irradiation. The underlying mechanisms of the identified actions and their potential applications to buildings are presented in Table 3.

4. Conclusions

Water management mechanisms in nature have special morphological features and occasionally involve active means for efficiency. A framework for water management strategies that enhances the identification of mechanisms for potential application to buildings is presented. The framework encapsulates key functions, corresponding processes, applied morphologies, with demonstrative examples from nature. In nature, the skin has a significant role for water management, so that organisms inhabiting arid regions have adapted distinct surface morphologies for condensation, which can be applied to buildings for moisture harvesting. The morphologies are not complex in their nature, rather have distinct forms, scales, and compositions. Thus, manufacturing new systems of similar functions is possible through adapting comparable physical rules.

One main objective of this paper is the systematic representation of the biophysical information for water management promoting the search for mechanisms to inspire new solutions for buildings. This information is summarized in the tables that abstract the broad information into several functions, processes, morphologies, and actions, and indicate their potential application in the building context. The relatively small amount of studies on biomimetic water management solutions for building applications has left a significant territory awaiting its grounds to be broken, and further research is required to test and validate the potential applications at the building scale.

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