Design process of a water reclamation garden: from natural niches to urban environment

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Abstract: Water reclamation gardens have existed for more than 20 years, combining wastewater process technology and botany to provide wastewater treatment. In these facilities, the boundary between functional gardening and sanitation/water reuse infrastructure is blurred. They use lower footprints than engineered wetlands and can be constructed in urban areas as they do not look or smell like conventional industrial facilities, while providing water treatment on the same scale. These gardens produce treated wastewater, while at the same time provide green and blue access to the community. Treatment can be more effective and adaptive using decentralized systems, where facilities are closer to the waste origin, in this case municipal areas, thereby minimizing costly infrastructure (piping network). For this to work, the treatment units must gain far more public acceptance, and a well-designed and functioning water reclamation garden helps this purpose greatly.

There are three main considerations in designing garden facilities: one is climate. It is necessary to determine whether the local climate can support a reclamation garden or whether an artificial microclimate is needed. The species arrangement is primarily defined by the wastewater treatment process. Plants rooted in the wastewater encounter different environments as the treatment process advances. This phenomenon further delimits available species. Selection is based on equivalence of the original plant habitat to the designed treatment phase and conditions. Considering the needs of the community, the local garden and architectural style defines what a community sees as acceptable or pleasing, sometimes even on a subconscious level. Knowledge of the local gardening trends and cultures helps creating gardens which will then be an integral part of a city’s urban fabric.

Based on the aspects described above, a methodology for a three-layered comparative design practice is introduced, linking wastewater process knowledge, ecological knowledge and information on stylistic trends. Utilizing these tools provides a solid foundation to answer all these demands and builds a foundation for long-term sustainability.

1. Introduction

Water use is an essential feature of our communities. Most means of water utilization result in production of wastewater, which causes severe environmental and hygienic hazards if left untreated. Treating wastewater is crucial for survival of most species, including humans.
There are several technologies developed for treating wastewater, all of which can be separated to preliminary, primary, secondary and tertiary treatment methods. Preliminary treatment is necessary for removing any substance which is harmful for the oncoming treatment phases. In primary treatment a physical operation is used to remove the floating and settleable materials found in wastewater. In secondary treatment, biological and chemical processes are used to remove most of the organic matter [1]. Secondary treatment also has a purpose of removing potentially harmful nutrients, for example N and P. Tertiary treatment is used for removal of residual suspended solids and nutrients and provide for disinfection [1]. The facilities involving water reclamation gardens serve the goals of secondary treatment, organic and inorganic nutrient removal. There are numerous technologies used for this purpose. For the ease of understanding we divide these methods to industrial technologies and treatment wetlands, as these are the main competitors of water reclamation gardens.

Industrial technologies require an extensive set of buildings and machinery. The removal of dissolved and particulate contaminants is accomplished biologically using a variety of microorganisms, principally bacteria [2]. These processes take place in reactors – basins, containing the liquids and the microorganisms responsible for the treatment.

Modern treatment wetlands are man-made systems that have been designed to emphasize specific characteristics of wetland ecosystems for improved treatment capacity [3]. They usually require extensive area but very basic technology, feasible for applications in smaller communities or treating water outside inhabited areas. These are artificial swamps, utilizing the soil (bed) and the settled biology (mostly plants) to keep up a microbial community in order to remove contamination.

Water reclamation gardens are merging these two. They are the living parts of a complex biological wastewater treatment facility design methodology, combining plants and industrial technology. These facilities use lower footprints than wetlands and can be introduced into urban areas without looking like industrial facilities; while providing water treatment on the same industrial scale. These gardens are placed directly on top of modified industrial treatment reactors and contain elements of a treatment wetland: a supporting media bed and a variety of plants. The quality and amount of the media used for the purpose is strictly limited, with the aim to force the plants to extend their roots into the surrounding wastewater. These roots develop a biofilm cover, a collection of microorganisms selected by root extrudates altering quorum sensing (bacterial cell-to-cell communication)[4], partially supported by O2 from roots [5]. This biofilm enhances the cleaning process, allowing reactor vessels designed to be smaller, reducing the necessary footprint. The plantal O2 supply reduces aeration energy demand.

Mixed vegetation in a reactor emptied for maintenance, revealing roots (Heyuan, China, 2018)
There are two basic methods of water treatment: batch and continuous. During the processes there are different stages. The treatment process changes the quality of the wastewater, creating a different environment in each stage. It means that plants must meet different circumstances, separated by either time or space. Time separated changes are easier to respond for the plants, as the technology allows the different influences to balance each other (e.g. low O2 levels are followed by periods allowing ample O2 to be accessed). Continuous technologies with space separated stages changes hold a different challenge. This method creates certain niches in certain reactors, with usually stable but demanding circumstances. These circumstances include, but not limited to continuous water coverage of the root zone, limited available O2 in the rhizosphere, overdosing of several nutrients and elimination of others, horizontally moving media, daily and yearly changes of constituents. As time separated methods require more reactor space the continuous method is significantly more widespread, and most of the water reclamation gardens are connected to these.

The water reclamation gardens are in use under most climate zones. Plantal life is not possible everywhere on Earth without altering several environmental components, namely temperature and irradiation. It is possible to alter these using greenhouses or heat/light reflecting structures. These structures require additional investments in proportion to the protection they offer. Adapting the designs to different climatic features is a challenge. The set of available species is limited: due to climatic and process features only certain plants are feasible for utilization aiming water treatment. These are mainly wetland species; their tolerances and preferences should be considered before application. Their natural habitat holds very significant information: the best survival/growth results could be achieved by finding plants that naturally occur in niches having features that can be found created artificially in the treatment process (e.g. water coverage frequency and duration, pH, Oxidation-Reduction Potential). The climatic and process requirements should be considered together when defining species for a plantation. This further delimits the number of available species.

Water reclamation gardens are mostly open to public; among others it is one of their purposes. They need to be open: a transparent, tidy and well-kept system changes public perception. They serve as public parks, places for recreation or educational centers. They draw attention to water usage and the necessity to clean it properly, while allowing space to use for citizens. Designing an open facility requires more than process and climatic considerations. Local garden building trends should be considered, as the result will have to blend into the fabric of the present rural environment. The transformation from liquid waste to reusable water happens in front of the visitors’ eyes.

Increasingly more people are migrating to cities [6], and the inhabited area is continuously growing. Most sewage treatment systems are built outside of towns due to unwanted features like smell, sight, heavy freight traffic. These facilities are usually very large, with capacities enough to treat all or most wastewater originated from the settlement. These installations resultingy require extensive, vast sewage systems, often with lifting stations. These conveyance facilities often cost far more than the actual treatment plant; in addition, the long pipelines create longer HRT (hydraulic retention time) in sewer systems, resulting in anaerobic conditions which adversely affect the wastewater: intensive smell and sometimes increased difficulty in treatment [7]. These big facilities are designed for decades (the unofficial industrial standard is 30 years). This time is more than enough for the habited area to grow around them. The solution for the problem can be decentralized wastewater treatment systems. These utilize numerous, smaller facilities treating water from smaller collection areas, closer to the waste origin, the people. Successful demonstrations of decentralized concepts and technologies and urban reuse applications, and educational outreach may offer viable alternatives to many urban water/wastewater utilities facing similar wastewater management issues related to costs, infrastructure, watershed protection, and conservation of drinking water supplies[8]. These decentralized water treatment installations may utilize different technologies. Among these -due to already discussed reasons - water reclamation gardens seem to be the most feasible.
For appropriate water reclamation garden process considerations, climatic requirements and cultural background must converge in a design which is functional, sustainable and attractive.

2. Methods
The design process requires collecting information about the target geography, the water treatment process intended to be used and the local cultural trends; these are merged to create a proper design.

2.1. Climatic research
The climatic research starts with studying geographical climate. Most of the available plants we can use are wetland originated, or accustomed to nutrient and water abundance. It is not a problem under Subtropical and Tropical Climates, but can be a challenge under Temperate and Arctic Climates, as wetlands there are populated by deciduous plants. In general, the evergreen species are more important on dry sterile sites and the deciduous species on mesic fertile sites [9]. If we don’t use shelters in areas where Winter temperatures drop below 10°C, we have to accept that the water reclamation garden will completely or partially lose foliage in the winter. The geographical climate is general, while microclimate is a set of environmental features different from it, and should be considered too. The geographical climate study includes the absolute average, possible minimum and average daily minimum temperature, the irradiation features and wind conditions. Microclimate can be altered by using greenhouses or other means of protection. Differentiating wastewater temperatures from average air temperature we can determine the $\Delta T$ between the water and the ambient air; if the differential exceeds 10-12 °C, based on experiences a shelter is necessary to ensure survival. High wind conditions might require protection of the plants regardless to temperature.

After deciding whether or not to use a shelter the design process will branch:

A shelter is required - Shelter types may utilize the following options:

- Greenhouse: an insulated structure, with or without heating but overall having a very good potential for microclimate regulation. Temperature, humidity, light and air exchange is strictly regulated. Greenhouses allow maximal flexibility in species usage: they offer climate independent design options. Installation, operation and maintenance costs are considerable.
- Heat Reflecting Structure: a tensile structure with a good level of heat reflection. It offers habitable area in extremely hot climates as the Sahara of the Arabian Peninsula. It helps maintain frost sensitive population under Subtropical and Temperate Climate. It offers limited but wider plant selection flexibility than not using them.

A shelter is not required. In this case, the design must accommodate for more environmental requirements:

- Temperature: the plants to be selected should originate from the same Climatic area.
- Wind: the species selection, maintenance and overall stand shape should be implemented to tolerate and/or deflect strong winds.
- Precipitation: if snow or ice is expected species should be selected and maintained to survive these conditions.

2.2. Process features
The process knowledge should include several water treatment-related topics, as follows:

- Batch or continuous process
• Process setup, number and position of aerated and not aerated reactors
• Aeration points, pipes, probes and other surface objects
• Entry and exit points of treated water
• Access roads
• Influent/effluent water properties, such as
  • Temperature
  • ORP, Oxidation Reduction Potential
  • BOD, Biological Oxygen Demand
  • TN, Total Nitrogen availability
  • TP, Total Phosphorus availability

These define the narrowed clusters of species to use, marking their target areas in the water treatment process. The plant species we use are coming from different habitats, shaped by the local macro- and microclimate, forming a set of tolerances and preferences. They are mostly natural wetlands, areas, where soils are water-saturated for a sufficient length of time such that excess water and resulting low oxygen levels are principal determinants of vegetation [10]. These have counterparts in the water treatment processes, for example:

• Fens: waterlocked, alkalic, nutrient-rich wetlands, usually forming on slopes, populated by herbs. Their counterpart is at the beginning of the process, with raw wastewater, low in dissolved oxygen but with abundant nutrient content. They are available for anaerobic reactors.

• Bogs: waterlocked, acidic wetlands, poor in nutrients, very low ORP. They usually form in depressions and populated by Sphagnum mosses, herbs and bushes, sometimes at higher elevations. Their technology counterpart is post-denitrification anaerobic reactors.

• Estuaries and flood basins: intermittently flooded, nutrient-rich wetlands with a lot of available nutrients. Their most likely counterparts are sequenced batch reactors, with time-based treatment phase separation. They contain a huge number of species, trees, bushes and herbs as well.

• Billabongs or backwaters: continuously flooded, nutrient rich water bodies with changing dissolved oxygen: they resemble of the continuous systems’ aerated reactors used for BOD removal. Their vegetation includes trees, reeds, herbs and low, sometimes floating plants.

• Marshlands: wetlands fed by brackish or saltwater, forming a habitat rich in nutrients and species of every kind, but most of them tolerates high salt content. Their counterparts are reactor systems treating wastewater containing seawater infiltration or industrial wastewaters with relatively high salinity.

• Meadows: intermittently flooded areas mostly inhabited by herbs, with high oxygen availability, good nutrient supply. They provide similar conditions like the latter-staged TN removal reactors.

The water reclamation gardens operate as hydroculture, so the soil features of the listed habitats should be roughly equivalent of the liquid in contact with the plant roots in the system.

2.3. Cultural and historical background

Cultural and historical background knowledge of contemporary garden building practices provide a good basis for functional and aesthetical arrangement. A plant list is just a list, a collection of species, but not a garden. As Gertrude Jekyll wrote:

"I am strongly of opinion that the possession of a quantity of plants, however good the plants may be themselves and however ample their number, does not make a garden; it only makes a collection."
This does not constitute a picture; and it seems to me that our duty we owe to our gardens and to our own bettering in our gardens is to use the plants that they shall form beautiful pictures; and that, while delighting our eyes, they should be always training those eyes to a more exalted criticism; to a state of mind and artistic conscience that will not tolerate bad or careless combination or any sort of misuse of plants, but in which it becomes a point of honour to be always striving for the best [11]."

To form them into a garden it is necessary to understand what is natural to a citizen of a certain location. An Arabian design may prefer a straight, lengthy alley, sides mirrored, something important at the end of the path, opposite the entrance. A Chinese design may opt for a series of enclosures, surrounded by tall walls of plants, forming small clearings, each containing something meaningful. A British design may enjoy a landscape close to natural vegetation, but rich in irregular shaped patterns, a French design most likely would favor order and logic. Knowing these require immersing in the local contemporary and historical landscaping cultures. The result -mostly due to technological restrictions- will never be the same what a local or a locally trained /experienced designer would design, but it will resemble it. It helps acceptance, and acceptance helps these facilities to be built and maintained, achieving wastewater treatment closer to the community members, ensuring sanitization while providing green and blue access.

3. Results
The discussed experience and gathered knowledge resulted a three-layered design process; it starts with gathering all relevant climate data and client needs, leading to a decision of creating an artificial microclimate or leaving the garden exposed to the environment. The climate study helps us outline a species list of relevant plants with local, native and endemic species.
local is everything what can be found in the location, anywhere: on the street, in the shops, on the fields.

Native species are the ones which were found in the location naturally or naturalized very long (for example a thousand year) time ago.

Endemic species are found only in the location in consideration and nowhere else.

After determining the species for the chosen microclimate, the water treatment process must be considered to find appropriate plants among the ones selected. For this it is necessary to understand how water changes during the treatment process, as plants are literally living in it- instead of soil. These features outline certain habitats, all of these containing species which will most likely survive immersion in different stages of the treatment process. Gathering this information enables the set-up of a narrowed cluster of species focusing on successful adaptation. In case of space separated continuous processes, this list already contains an order, which marks the exact areas for certain species.

The plant list provides building bricks for creating an outline shape for the stand and form it in line with the local cultural heritage. The proper shape is defined by the exposition to climatic elements (irradiation and wind conditions in case of open installation). Preferred overall garden shape is a waveform, directing the wind above and near the open stand, while ensuring that all plants have adequate access to sunlight both in open stands and in greenhouses. Operation and maintenance need to shape design further. Cultural considerations will define space, outline and symmetry and defines the colours and certain species used.

The final result of the process developed is a sturdy and lively garden, thriving in wastewater. The finished water reclamation gardens are subject to continuous monitoring, refining knowledge about plant position in systems in accordance to process, maintenance and plant protection methods. Success of a design is considered based on the user feedbacks received.

4. Conclusions
There is continuous and growing need for implementing wastewater treatment closer to its source of origin. This requires wastewater to be treated in a way which is acceptable and appropriate for the community, providing community access instead of insulating the facilities from them. Utilizing plants in general has a surprising effect: a bare room with a bouquet of flowers becomes a bouquet of flowers -surrounded by a room. In other words, the presence of natural plants distort perception, and if they are used in the appropriate proportion and density, they will be the focus of the attention: the facility, which once held the main importance (the industrial process), around the garden is perceived merely as a shell, a container, framing a garden. This altered perception greatly helps localizing wastewater treatment closer to the citizens personally.

The goal of the developed comprehensive design methodology is to meet the requirements of designing a sustainable water reclamation garden for the combined biological wastewater treatment process, getting it closer to the community members in two ways:

- Literally, as a shorter distance can be applied as reclamation gardens have more acceptance. It results in saving on installation works, getting better treatment results and reduced environment load; both during installation and operation. This implies better sanitation and improving treated water quality and energy efficiency. All these are in line with the United Nations Sustainable Development Goal no. 6, Clean Water and Sanitation, as this way (6.3) water quality is improved by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, reducing the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally. The 9th SDG (Industry, Innovation and Technology) also applies: the water reclamation gardens are resource – efficient, sustainable technology (they create increased capacity on a smaller land area, and treatment capacity grows by time). It is a
very specific use of these gardens (9.4.) upgrading infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes – a considerable number of projects are finished with this approach.

• Figuratively, as the water treatment process can be accessed in an environment providing green and blue access (access to green areas and water body) at the same time, shaping an industrial process area to a community place. As SDG 11, Sustainable cities & Communities suggests, (11.3) water reclamation gardens enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in a number of countries. These gardens also create a new education and awareness for improving the understanding of the importance and methods of water treatment and reuse as SDG 13.1 Climate Action requires, while providing universal access to safe, inclusive and accessible, green and public spaces (11.7).

As the possible species selection choices and applicable patterns are delimited by the process and species availability, a systematized design approach is established. The applied design method is satisfactory but still requires further refinement. Applicable plant species are abundant; studying cultural background requires continuous attention, as garden building trends and social patterns (as political and belief systems) are constantly changing.

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