

Review

Design of Land Application Systems for Water Reuse

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Abstract: Water reuse via land application is old technology; but the water balance only design approach and practice has not worked well. There are many benefits of water reuse by irrigating crops; however, there are some risks if not designed properly. When the design approach uses a combined water-nutrient-salt balance, the most effective and sustainable, long-term system is achieved. This approach provides a design based on land area requirements, on-site water storage, and economic return from the irrigated crops. The single, most often overlooked step in the water balance is accounting for the water stored in the soil. When spread over large areas, this quantity of water results in considerably less required surface water storage, which saves capital costs. This design approach has been used successfully on multiple sites for over 30 years without failure.

Keywords: wastewater; recycle; beneficial use; irrigation; mass balance



Citation: Fedler, C.B. Design of Land Application Systems for Water Reuse. *Water* **2021**, *13*, 2120. <https://doi.org/10.3390/w13152120>

Academic Editors: William F. Ritter and Akintunde O. Babatunde

Received: 12 May 2021
Accepted: 28 July 2021
Published: 31 July 2021

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1. Introduction

Reuse of water on land has been practiced for many years and may be the oldest approach to treat and dispose of wastewater [1–3]. Land application of wastewater is generally defined four categories, slow-rate, overland flow, rapid infiltration, and on-site or individual home systems (which is a type of slow-rate system) [4,5]. The slow-rate system is the most often used for treating municipal wastewater and therefore, is the emphasis of this review.

Land application of wastewater is defined as applying a known quantity and quality of wastewater onto the land surface to achieve a specific level of treatment and disposal by natural physical, chemical, and biological processes that occur within the plant-soil-water matrix [6]. Treatment and disposal by land application has been widely accepted as a cost-effective means to process wastewater [7]. An additional benefit of irrigating cropland with wastewater is the reduced demand on freshwater resources [8–10]. This is especially important in arid and semi-arid regions where fresh water is scarce. The advantages of water reuse as crop irrigation water include low cost compared to mechanical treatment methods, revenues from the produced marketable crops, freshwater resource conservation by replacing fresh water for agricultural irrigation, and protection of surface water resources from potential nitrogen contamination by decreasing wastewater discharged into surface water bodies [11].

With the many benefits of water reuse by irrigation, there are a few risks. The primary concern is potential groundwater contamination with nitrate often caused by excessive leaching [12]. If excess nitrogen is leached below the crops' root zone, the potential for elevated nitrate concentrations could affect the drinking water, which can cause several health issues such as methemoglobinemia, gastric cancer, non-Hodgkin's lymphoma, infant mortality, central nervous system birth defects, and hypertension [13]. Accordingly, nitrogen is often regarded as a limiting design constituent when designing and operating a wastewater land application system [4,14]. In addition, salt accumulation in the soil [15] and potential changes in soil properties [16] are of concern with land application systems that should be considered. Contaminants of emerging concern, such as pharmaceuticals [17], are receiving attention due to plant uptake and the potential for entering ground water

supplies. In general, when designing land application systems as a final disposal of treated wastewater, careful consideration should be given to the applicability of the reuse potential with respect to emerging contaminants present in the water source.

When designing irrigation systems to reuse water there are many factors that need to be considered; but one of the important factors is the approach. In terms of approach, the design engineer must remember how agricultural practices occur while similarly the agronomist must remember the overall goals of the land application system. The engineer needs to consider good agricultural practices to maintain an effective and sustainable land application system; and, the agronomist must understand that the purpose is the treatment and disposal of the wastewater and simply maximizing profits is not the only concern. One of the more recent approaches used to optimize water reuse is artificial intelligence (AI) [18]. One of the limitations of using AI is the design approach required in the analysis. If the design approach is not complete, then using AI will be somewhat ineffective.

Other factors required in the design of the reuse system include the fate of nitrogen, the effects of salts on crop growth, and the management of salts with proper irrigation scheduling that accounts for required leaching. In addition, the processing of organic matter in the wastewater greatly affects the control of odors that can come from the irrigation with the wastewater. The bottom line is that there is a strict balance between the water, nutrients, and salts applied and how each of those items are processed and managed.

2. Design Approaches

Reed et al. [4] and USEPA [19] presented two basic design approaches to land application of wastewater. The first approach was called Type I in which the maximum amount of water was applied so that a minimum amount of land would be required. This type of system was often limited by the hydraulic capacity of the soil for municipal wastewater sources. The second approach was called Type II in which the water applied was just enough to supply the crop water needs to maximize the land area covered. In this case, the water loading rate determines the land area required. Similarly, Johnson et al. [14] used the concept of land limiting constituents to limit the application rate based upon the one constituent in the water that limits the rate and total application of the water.

Fedler and Borrelli [20] first presented an alternative design approach based on a water balance. This approach was later improved upon by Fedler [11] to include both a nitrogen and salt balance that was validated by Duan and Fedler [21]. The water balance is defined in Equation (1).

$$SM_i = SM_{i-1} + P_i + I_i - ET_i - L_i \pm S_i \quad (1)$$

SM_i is the initial soil moisture for month i , SM_{i-1} is the soil moisture in month $i-1$, P_i is the precipitation for month i , ET_i is the evapotranspiration for month i , L_i is the leaching for month i , and S_i is the water going into and out of an external storage basin that is typically required for annual operations. The units for each term are length or depth per time, such as cm/month. It should be noted that the soil moisture during any month cannot be less than zero nor more than the water holding capacity of the soil within the root zone of the crop. Soil moisture is determined by the water holding capacity of the soil and it is a function of the soil type. These data should be obtained from local agricultural extension services or the Web Soil Survey (<https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>, accessed on 9 May 2021). Storage is required for a land application system because water enters the system daily at a near constant quantity while that used for irrigation varies monthly depending on crop water needs during the growing season. Leaching is defined as any water that is applied in excess of the soil water holding capacity.

2.1. Leaching Requirements

Leaching of salts from the root zone is required and is especially important when applying wastewater because of the typically high salt levels in the water compared to other sources of irrigation water. When planning for leaching, a common approach is to

provide that leaching over the entire annual application of the water. Unfortunately, in arid and semiarid regions this is difficult to achieve because the evapotranspiration rates are high leading to difficulties in delivering the required quantity of water. In addition, the differences in hydraulic conductivity and water holding capacity of the soils may limit the rate at which the water is applied. Continuous leaching is a common misconception. Therefore, seasonal leaching should be considered to maintain a proper salt [22,23].

Another misconception when designing irrigation applications for wastewater is that full crop production is required. If the concentration of nitrogen in the water is high, full crop water requirement may be difficult to achieve. The procedures recommended by Ayers and Westcot [24] have been used successfully for many years. Their procedure allows the designer to determine the leaching requirements for various degrees of yield reduction as determined by the total dissolved solids concentration of the water applied. Thus, sometimes it is necessary to allow for less crop production, which also means less nitrogen uptake, to achieve an appropriate water balance for the system.

As can be seen in Equation (1), water storage will be necessary to achieve year-round application, which is necessary in the design of a land application system [4,19,25]. Another point to note with the mass balance design approach (Equation (1)) is that the rate of irrigation is constant while the amount of leaching achieved is variable from one year to the next and depends on the level of precipitation. This contrasts with the constant irrigation and constant leaching design approach used by the Texas Commission on Environmental Quality [26] that requires additional storage since the method allows for full crop water requirements plus full leaching for every year. With this approach water during wet years is stored for use in dry years. Another approach used by Reed et al. [4] can be defined as the constant leaching and variable application design. Each of these three approaches have their advantages and disadvantages. For example, the TCEQ approach always provides the full water requirements for irrigation and leaching but at the cost of installing additional storage. The mass balance approach in Equation (1) will minimize both land area and storage by accounting for the water stored in the soil. The disadvantage is that additional management is required to track both the irrigation provided and the calculated leaching achieved and adjusting the applications if long periods of drought due to climate change occur. The constant leaching and variable irrigation approach results in less storage than the TCEQ method but allows for the maximum nitrogen to be leached while not exceeding drinking water standards. However, this is not a long-term, sustainable approach. This approach is similar to Lynch and Kirshen [27] who considered optimizations techniques to provide management of the system. Their approach only considered the basic water balance with no consideration for soil water storage, nitrogen leaching, nor the effects of salts.

When using Equation (1), the precipitation data required for design analysis is monthly data for the previous 25 years, or more if available. Using the average monthly precipitation data for completing the main water balance, the application rates resulting are then used to analyze the resulting leaching for each of those 25 years. This analysis provides the designer with an understanding of the years in which full required leaching is not achieved. The rule of thumb for arid climates is that there should never be any 5-year window where the average required leaching was not achieved. If the long-term data analysis shows this to occur, then the application rates should be adjusted upward in the main water balance to achieve additional leaching. The results should be rechecked by running the long-term analysis with the newer application rates.

2.2. Evapotranspiration

Of course, the water balance cannot be computed without appropriate evapotranspiration (ET) data for the specific location of the application site. There are many methods to calculate ET and each requires different climatic data [28–33]. Equations used to calculate ET are as simple as temperature based [32] or radiation based [33] to the more complex

combination methods [34] requiring numerous climatic variables including solar radiation and vapor pressure deficit.

The best available technology should be used for the data available at the specific location considered because the predictive capability of the various methods varies widely. Single variable models are less than 80% accurate while combination models are as good as 95% accurate. If ET is underestimated, the results for a land application system are greater required land area and less crop production. Over estimating ET can lead to wet conditions and potential crop diseases and poor wastewater treatment, which often leads to odor problems. In addition, the designers must also make sure they are aware that all ET models were developed with either a grass reference or an alfalfa reference so the appropriate reference crop coefficient may be used accordingly.

3. Understanding Nitrogen

Over the past two decades, advancements in understanding the fate and transformation of nitrogen in agricultural cropping systems have been achieved [35]. Nitrogen takes on many forms depending upon the level and type of treatment it receives prior to irrigation. If the treatment system is primarily anaerobic, then high levels of ammonia nitrogen may be present and denitrification and plant uptake are the primary removal mechanisms. If treatment is aerobic, then the primary form of nitrogen is nitrate and plant uptake is the primary removal mechanism. In either case, these water-soluble forms of nitrogen will affect the irrigation scheduling to minimize nitrate leaching into the groundwater beneath the application area.

Total Kjeldahl nitrogen (TKN) in the soil is an indicator of nitrogen storage in the soil as well as being an important indicator of soil fertility and soil quality [36]. Fedler [11] examined a land application site over a period of one year to evaluate the fate of TKN in the soils.

The fate of soil TKN was examined on an existing land application site over a period of one year where the various plots had been irrigated with aerobically treated municipal wastewater for 10 to 69 years [37]. The soil types on the plots consisted of Amarillo Fine Sandy loam, Acuff Loam, Estacado Clay Loam, Friona Loam, and Mansker Clay Loam. Details of the site map for these plots can be found in Fedler [11]. Irrigation water samples of the water applied to the three plots were collected and tested for total nitrogen (TN), nitrate-nitrogen ($\text{NO}_3\text{-N}$), ammonia-nitrogen ($\text{NH}_3\text{-N}$), and total Kjeldahl nitrogen at two depth ranges, 0 to 15 cm (Depth 1) and 46 cm to 61 cm (Depth 2). The wastewater application rates used during this study were based upon the water balance design approach.

For the upper soil depth (Depth 1), the only significant difference in the soil TKN occurred in the soil with the higher clay content. For the lower soil depth (Depth 2), there was not significant difference among any of the plots. Soil TKN includes organic nitrogen and ammonia or ammonium. Nitrate nitrogen, on the other hand, is negatively charged and is not readily retained in the plant root zone due to its charge's repelling force. Nitrate nitrogen can move beyond the plant-root zone when the soil water content is more than field capacity. Organic nitrogen in soil can be mineralized [38] and converted to ammonia or ammonium. Ammonia nitrogen can be transformed into nitrate nitrogen by nitrifying bacteria [39] and to nitrogen gas or nitrous oxide which is released into the atmosphere through the denitrification process [40]. Ammonia nitrogen and nitrate nitrogen can be taken up by plants and soil microorganisms in the immobilization process [41]. Ammonia nitrogen can be released into the atmosphere by ammonia volatilization [40]. Soil TKN will increase with the applied nitrogen from wastewater irrigation and decrease by plant and microorganism uptake (immobilization), nitrification, ammonia volatilization, and leaching.

Ammonia volatilization is determined by the quantity of ammonium or ammonia in the soil solution, soil solution pH level, and soil water content [42,43]. When the soil solution pH is higher than 7.5, ammonia volatilization becomes significant [42]. Ammonia

volatilization occurs when the soil water content is close to or at field capacity or when the soil undergoes slow drying for a few days [42,44]. Roelle and Aneja [43] confirmed that a peak ammonia emission rate happens during the drying period following a heavy rain event. They also found that temperature explained the largest variability of upper coastal plain soil ammonia emission. The pH values within typical West Texas soils and in applied wastewater effluent at the test site averages over 8.0 [45]. Tan [46] reported that an alkaline soil was dominant in semi-arid and arid areas. Therefore, the emission rate of ammonia at the three plots at the test site is determined by ammonia nitrogen availability, temperature, and soil moisture level. Mineralization, nitrification, and immobilization are highly dependent on soil moisture, aeration condition, pH, temperature, substrate availability, and soil texture and structure [47]. Physiologically, plants consume ammonia nitrogen before nitrate nitrogen and nitrogen uptake by plants is the primary cause for a decrease in soil TKN.

The soil TKN in both depth ranges was low from July to December, reached the highest in January, and then decreased from January to June to the lowest level close to that found in July to December. The higher soil TKN that occurred in January is likely attributable to low temperatures causing low ammonia emission and a low nitrification rate, in addition to reduced nitrogen uptake by plants. The gradual decrease in soil TKN from January to June reflected the combined effects of a gradual increase in temperature, nitrogen uptake by plants and microorganisms, nitrification, and ammonia emission on the resulting soil TKN. In addition, the low soil TKN is likely the result of the high soil moisture causing high ammonia emission and nitrogen loss due to leaching in the September to February time frame.

Environmental factors that affect the denitrification process in soils include soil moisture, temperature, and soil type [48]. The USEPA [6] states that denitrification rates between zero and 80% are not uncommon when irrigating with wastewater. Duan et al. [12] found that high soil temperatures can accelerate the movement of water, thus, changing the carbon and nitrogen mineralization and nitrification processes, both of which cause higher denitrification rates [49]. The denitrification rate found during the month of August was lower, but that was likely due to the hot and dry conditions that typically occur at that time in Texas. It was found that if the soil moisture was less than 15%, denitrification rates decrease rapidly. This means that soil moisture is the more important factor affecting denitrification, followed by temperature.

4. Additional Design Considerations

4.1. Methods of Irrigation

The methods of irrigation and their respective application efficiencies vary widely. Furrow irrigation is one of the least efficient methods from the standpoint of application efficiency; and, this is especially true if the furrows are longer than about 200 m. This method of irrigation should be used with caution. Side-roll sprinkler irrigation improves the application efficiency; but, these systems require more maintenance and operating time since they are manually moved. The center pivot system has an average application efficiency greater than 75% [50]; however, this efficiency can be improved with the inclusion of the low energy precision application devices. No matter which method of irrigation is used, the application rate must be tied to the hydraulic conductivity of the soil and changes in that soil property must be considered [23,51].

When considering the application efficiency of the sprinkler system of choice, it is recommended that that average annual efficiency be considered. When individual, seasonal tests are conducted on a sprinkler system, the application efficiency can vary between 40% and 60%. When the data for the year of tests are added together, the application efficiency could increase to as much as 80%. This increase in the annual application efficiency is a result of the changes in wind speed and direction that occur throughout the year and the resulting changes in application depth that occur at any location from each sprinkler. Another factor to consider is the overlap of the sprinkler pattern. Tests were performed to

evaluate typical sprinkler heads used for solid-set irrigation nozzles used for wastewater effluent systems. It was found that if the sprinklers were positioned to maintain an overlap of reaching from one sprinkler head to another (typically called head-to-head overlap), the application efficiency would increase to over 80% compared to averaging 60% for an individual head sprinkler pattern [52].

4.2. Crop Selection

Identifying a crop to use on the land application site for reusing water involves many considerations. The first item to consider is water consumption. It is always advisable to consult with local agricultural organizations to obtain a list of potential candidate crops. To obtain the more efficient design, crops that consume large quantities of water reduce the size of the site. However, a single crop system is often not possible and often not advisable because crop rotation is necessary as part of good agricultural practices. For a large-scale system processing more than 3800 m³/d, the better option is a two-crop system such that at least 25% of the land can be rotated at least once every four years.

Next, the active growth period of the crop should be considered. Annual crops such as alfalfa or grasses are good since planting and harvesting periods are minimal. Seasonal crops such as corn, wheat, or soybeans have specific growing seasons such that two crops, a winter and summer crop, need to be grown to maximize the water applied annually. For the two-crop system, two factors affected the water balance. First, time to allow for planting and harvesting must be considered and that reduces the water application during those periods. With the two crops used, application rates need to be adjusted to account for the nitrogen applied which is also affected by the potential crop water consumption during the planting and harvesting phases of growth.

If grasses are being considered, one option is to use both cool and warm season grasses together to maximize the crop water consumption. This is often achieved by over-seeding each seasonal grass to maximize biomass produced. Remember, the more biomass produced, the more nitrogen uptake occurs as well as the more water that is required. Lastly, as discussed above, the nitrogen uptake by the plant and the salt tolerance of the crop must be considered as part of the selection process. If the salt tolerance is low and a reduced growth of the plant is selected, recalculating the nitrogen consumption is also required. Typically, during the active portion of the growing season, the relationship between biomass production and water consumption is linear. Therefore, if the depth of application is reduced by 10%, then the nitrogen uptake is also reduced by 10%.

4.3. Available Water and Irrigation Scheduling

As the irrigation schedule is determined from the water balance for a specific application, the designer should consider available water and readily available water. In the plant-soil-water system, the soil will retain water. The water available is that water between field capacity and the permanent wilting point. Naturally, it is not advisable to operate the soil water content near the wilting point.

When calculating the water balance and determining soil moisture and leaching, the recommended approach is to consider readily available water, which is defined as half the total available water in the soil. When this approach is used, the soil water storage allows for easier leaching because less water is required to obtain the desired level of leaching. The benefit of this method of operation is that when a precipitation event occurs and leaching results, the leach water is at its highest quality (with respect to salt and nitrogen concentrations) level thus reducing the potential negative impacts on the groundwater. This is especially important in arid and semiarid regions.

5. Conclusions

Reuse of water on land to grow crops is one of the oldest technologies used to treat and dispose of wastewater. In the beginning, little consideration was given to the various constituents within the water that could negatively affect the natural environment; but,

that was because application rates were generally so low that potential problems did not exist. Later, when more water was being applied to smaller areas, the science behind understanding the various constituents being treated increased. With this increased knowledge about the land application systems, better design approaches were developed. During this period of growth, land application of municipal wastewater has been viewed as both the best technology and the worst technology to utilize. Much of the negative attitude stems from a lack of understanding of the more important design factors required to provide optimal performance. In addition, understanding the different climatic factors and how they change the design approaches were not well understood.

The water-nutrient-salt balance design approach has proven to be an effective design approach from the standpoint of land area requirements and on-site water storage. This approach begins with completing a water balance that considers water applied, precipitation, effective leaching, crop consumptive use (evapotranspiration), and soil moisture. The soil moisture storage is often the one critical step omitted from other design approaches; and, as such, it does not allow for an optimal design, especially when considering the land area and quantity of storage required, which are usually the two largest cost components of a system. Runoff water from the site is often overlooked, but the most sustainable and efficient operating land application system should never allow runoff to occur.

Although one land application system with the longest-term, continuous operation located in Lubbock, Texas did not use the water balance design approach described by Equation (1) since its inception, it has used the approach since 1988. Since that time, the system has not only managed both the nitrogen and salt balances appropriately; but they were also able to reduce a high-nitrate groundwater mound caused by years of misapplication prior to the use of this alternative design approach by using that groundwater for part of their irrigation needs.

In the future, efforts to understand the total economic benefits of treated municipal wastewater reuse with land application systems will provide stakeholders with the information they need when selecting the best system for their operations. In addition, efforts need to be made to optimize the use of treated wastewater on land that include the three mass balances while considering factors such as distance of the application site from the pre-treatment site and type of pre-treatment system used (mechanical versus natural). The expenditure of energy required for the system must also be considered because the various pre-treatment systems require considerably different levels of energy. Lastly, for long-term use of the land application site, it must be sustainable without any negative impacts on either the soil or groundwater beneath the site. With the economic benefits defined and the optimized design approach clearly understandable, policy makers are provided with the information they require for developing future policies on water reuse options.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: This study did not include any publicly available datasets.

Acknowledgments: The author would like to acknowledge the support of the Civil, Environmental, and Construction Department for their support during the development of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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