Effluent Nitrogen Management for Agricultural Re-Use Applications

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Abstract
Utilizing treated domestic wastewater to grow forage crops is becoming commonplace in regions that cannot release effluent into oceans or rivers. A key concern when using disinfected secondary treated water is nitrogen percolating below the root zone and reaching the groundwater. A 2,000-acre wastewater reuse site with 27 center pivots in Palmdale, California is being utilized by the County Sanitation Districts of Los Angeles County to reuse approximately 8 to 9 million gallons per day of treated wastewater from the city of Palmdale. Through the development of a daily soil water/nitrogen balance model, combined with an overall cropping and monitoring strategy, the nitrogen deep percolation has been minimized throughout the reuse area to levels that are below Regional Board requirements.

Introduction
In the western United States, scarce fresh water supplies have led to increased utilization of treated wastewater for a multitude of purposes. Historically, wastewater was treated and either put into rivers or oceans, percolated into the groundwater, or allowed to evaporate. However, water quality and quantity concerns have led to more innovative disposal techniques. In many areas treated wastewater is being utilized to irrigate landscapes in parks and golf courses. In communities surrounded by agriculture, the treated wastewater is being used to irrigate crops that are not used for direct human consumption (such as forage crops).

In Palmdale, California, the County Sanitation District No. 20 of Los Angeles County (District) received a Cease and Desist order from the California Regional Water Quality Control Board, Lahontan Region (Regional Board) in 2004 regarding application of secondary treated domestic wastewater with high nitrogen concentrations on agricultural fields near its treatment facility. At that time, the District had several center pivots and a flood irrigated field. The Regional Board objected to the volume of water and the concentration of nitrogen in that water, which was being measured in vadose zone measuring devices at the reuse area. In response to the order the Districts contacted the Irrigation Training and Research Center (ITRC) at California Polytechnic State University, San Luis Obispo, for recommendations on reducing the amount of nitrogen percolating below the crop root zone.

The recommendations provided by ITRC involved expanding the reuse area, replacing the flood irrigated field with additional center pivots, improving the distribution uniformity of the existing pivots and the overall design and sprinkler packages for new pivots, and improving the scheduling of irrigations using a daily irrigation scheduling program that allows users to plan for future irrigations using both a soil water and nitrogen balance.

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This paper will focus on the irrigation scheduling and annual crop planning aspects of the District's Effluent Management Site (EMS). The physical components of the system such as center pivot design, modifications, and maintenance will be addressed in a separate paper.

The following sections will:

- provide background for nitrogen and soil water balance components
- show how the individual components are brought into a real-time scheduling, planning, and monitoring strategy
- present the results of the strategy

Nitrogen Balance

The benefit of using treated domestic wastewater on agriculture and landscapes is that nutrients that are in the wastewater can be taken up by the plant and are removed from the reuse area. These nutrients – nitrate in particular – can pollute ground and surface water in high concentrations. The nitrogen cycle is depicted in **Figure 1**.

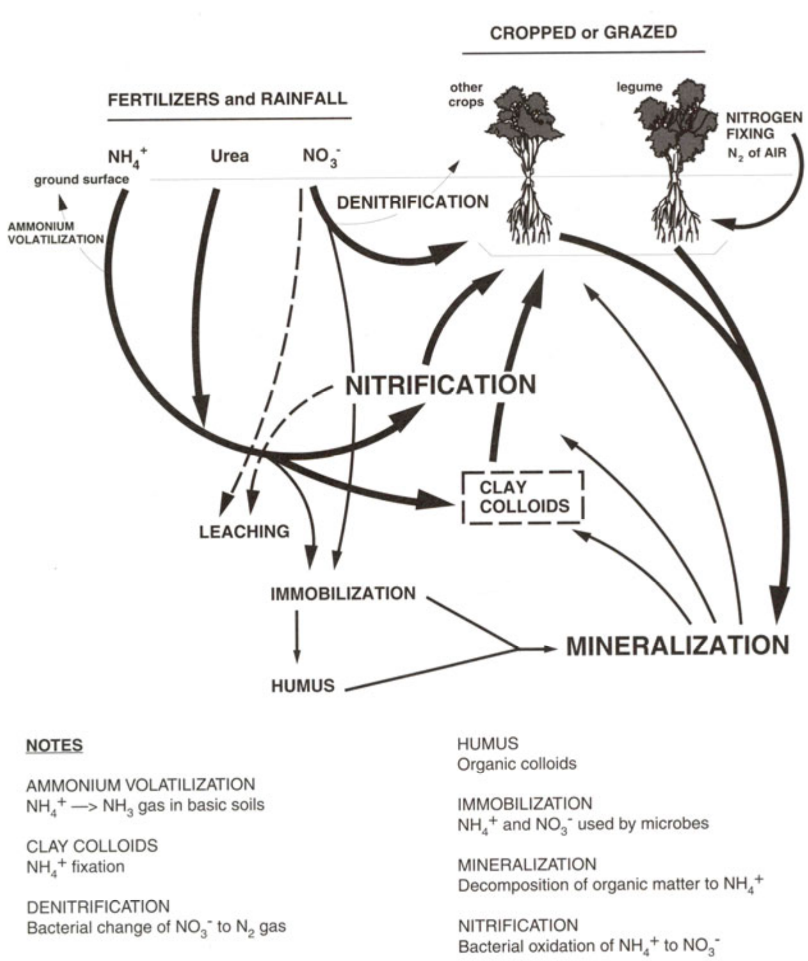

Figure 1. Nitrogen cycle (from Burt et al, 1998)

Sources of Nitrogen

There are two main sources of nitrogen at the Palmdale EMS:

1. Nitrogen from the effluent applied through the irrigation system subsequently taken up by the roots. This nitrogen can take three forms:
   - Organic nitrogen
   - Ammonium-nitrogen
   - Nitrate-nitrogen

   Organic nitrogen added to the soil via the effluent is converted by microbial mineralization processes into ammonium-nitrogen during the year. This ammonium-nitrogen will be rapidly converted into nitrate-nitrogen by the microbial process of nitrification.

2. Nitrogen from N_2 gas fixed during biological nitrogen fixation in the alfalfa crop by the *Sinorhizobium meliloti* bacteria. During biological nitrogen fixation, the microorganisms found in the symbiotic relationship with legumes such as alfalfa take the dinitrogen (N_2) gas out of the atmosphere and convert it into ammonium-nitrogen inside the alfalfa plants. This new ammonium-nitrogen is converted into amino acids and proteins to be used by the alfalfa plant. Nitrogen formed by biological nitrogen fixation within the alfalfa root not used by the plant is released into the soil and converted into nitrate-nitrogen as the roots die.

Nitrogen Removal

Nitrogen is removed from the EMS cropping system through four methods:

1. *Crop harvest* is the largest method of nitrogen removal in most cases. This is especially true with forage crops, because the majority of vegetation is removed at harvest. At the EMS, forage crops like small grain crops (wheat, barley, oats, etc.) are harvested for hay (vegetation and grain are removed from the field) along with sudangrass and alfalfa. Harvested tissue is analyzed at every harvest for nitrogen content. In addition, each load of harvested material is weighted so that the total tonnage of crop and nitrogen contained in that crop can be accurately estimated.

2. *Ammonia volatilization* occurs when ammonium converts to ammonia and enters the atmosphere. High temperatures, high pH, and high concentrations of ammonium and ammonia in the irrigation water can all contribute to higher percentages of ammonia volatilization.

3. *Denitrification* occurs when certain denitrifying bacteria commonly present in the soil are stressed for lack of readily available atmospheric oxygen gas (O_2) in the soil air. When the soil is irrigated or when rain falls, the water moves into the soil pores and tends to exclude the air from these same soil pores (Dinnes, et al, 2002). This water reduces the amount of oxygen gas in the soil. The nitrate-nitrogen (NO_3^-) contains an alternate source of oxygen (O) these special denitrifying bacteria can use for growth. As a result, the nitrate-nitrogen is converted into dinitrogen gas (N_2).

4. *Leaching or deep percolation* of nitrate below the crop root zone and eventually into the groundwater is a major source of pollution. The amount of nitrates leaching below the

root zone is one of the most difficult nitrogen destinations to measure. It is not reasonable to expect an accurate direct field level leaching measurement with today's technologies. Measurement units are limited by point measurements in a field that may not be "representative". Therefore, deep percolation is computed as a closure term in a water balance.

Calculations
The following equation shows the basic nitrogen balance calculation. Due to the topography, climate, and irrigation methods used at the EMS site, runoff is not a concern in this case; therefore, runoff is not included in the calculations.

$$\Delta Rz_{Storage} = \sum N_{inputs} - \sum N_{outputs} \qquad \textbf{Eq. 1}$$

where,

$\Delta Rz_{Storage}$ = Change in nitrogen storage in the root zone
$\sum N_{inputs} = N_{effluent} + N_{fixation}$
$\sum N_{outputs} = N_{Harvest} + N_{Volatization} + N_{Denitrification} + N_{Leaching}$

Method 1 – Limited Method
Since nitrogen leaching below the root zone cannot be accurately measured on the field level, it is moved to the right side of the equation (also known as the closure term). This modified equation will be referred to as **Method 1** for calculating nitrogen leaching or nitrogen remaining in the soil profile.

$$\Delta Rz_{Storage} + N_{Leaching} = \sum N_{inputs} - \sum N_{outputs} \qquad \textbf{Method 1: N Balance}$$

where,

$\sum N_{outputs} = N_{Harvest} + N_{Volatization} + N_{Denitrification}$

An accurate nitrogen mass balance in the field is complicated by the difficulty of determining the amount of biological nitrogen fixation in the alfalfa crop. Therefore, although the $N_{Harvest}$ is easy to measure, we do not precisely know what percentage of that nitrogen was fixed by the plant from the atmosphere, and what percentage originated with the wastewater. Because of this limitation with Method 1, Method 1 is only used for crops that do not fix nitrogen (grain hay and sudangrass at the Palmdale EMS).

Method 2 – Estimated Nitrate Leaching
No easy field test is available to monitor the amount of biological nitrogen fixation by the alfalfa. Since this can be a major source of nitrogen for alfalfa, the alfalfa fields require a different method (other than Method 1) of estimating nitrogen leaching below the root zone. This second method relies upon a detailed daily soil water balance to track water destinations and nitrate concentrations measured in soil water below the crop root zone.

Using the daily irrigation scheduling program with real-time data and accurately measured pivot distribution uniformity, the amount of deep percolation can be estimated across the field. Using the actual distribution uniformity, the program applies differing amounts of water across the field and can then determine the amount of deep percolation (leaching) that occurs at the different points. The program looks at five computed, hypothetical points in the field: the wettest, mid-level wet, average, mid-level dry, and the driest points. The distribution uniformity concepts and the irrigation scheduling program are described in the following sections.

Water Balance

Figure 2 shows "perfect" irrigation scheduling. It is "perfect" because the average depth of the lowest quarter (d_{lq}) equals the target depth of infiltration (usually the soil moisture depletion). As can be seen in the figure, even with a "perfect" irrigation schedule, deep percolation is inevitable – deep percolation exists on 7/8^{ths} of the field (Burt, et al, 1997). If the distribution uniformity (DU_{lq}) is improved, the amount of deep percolation will be lower. It is also important to note that with a "perfect" irrigation schedule, the lowest 1/8th of the field is being under-irrigated. This will cause some crop stress, but only minimally.

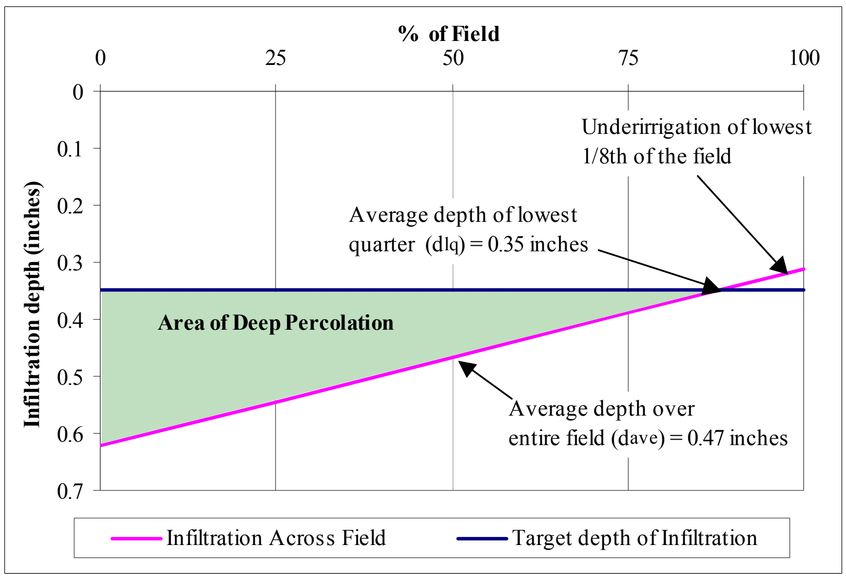

Figure 2. Simplified case of "perfect" irrigation scheduling. The DU_{lq} = (0.35/0.47) = 0.75. Note that the depth is the depth of water, not soil depth (from Burt, et al 1997).

In real-world applications, it is difficult to precisely estimate the target amount that should be applied (i.e., irrigation is not a perfect science). Soil moisture sensors and irrigation scheduling programs are two tools that are frequently used to help estimate the target. However, these tools have their limitations. For example, soil moisture sensors should be placed at representative points in a field – but unless the distribution uniformity is excellent, one never knows if the selected point is "representative". Making irrigation decisions by using weather data alone to estimate crop water use also has its limitations.

One can achieve very reasonable results using a combination of (i) excellent local weather data with a crop ET model, (ii) soil moisture measurement devices, and (iii) good records of the actual volumes and timing of water applied. This assumes that the irrigation system has been designed and managed for a good distribution uniformity. At the EMS, distribution uniformity and accurate water application records have been improved significantly since ITRC began providing technical assistance. The details of these endeavors will be saved for another paper.

Accurate weather data is considered the most important part of a good irrigation scheduling program. Initial ITRC recommendations included installing a California Irrigation Management Information System (CIMIS) weather station on-site. Prior to this, the closest station was in Victorville, CA, over 30 miles away. The California Department of Water Resources (DWR) installed the CIMIS station at the Palmdale EMS (Station #197) in the spring of 2005. This site is managed by EMS and ITRC personnel. Station #197 now provides weather data and the calculated ASCE Standardized (2000) Penman-Monteith grass reference evapotranspiration (ET_o).

Dual Crop Coefficient

Historically, crop evapotranspiration was calculated by adjusting the ET_o based on the actual crop in the field using a crop coefficient (K_c). A more accurate method actually adjusts the K_c values based on soil evaporation and crop stress that can occur. This preferred method of determining a crop coefficient (K_c) splits the computation into two components: transpiration and evaporation. This is called the "dual crop coefficient methodology" and is outlined in *FAO Irrigation and Drainage Publication No. 56* (Allen et al, 1998). An additional component – lack of soil moisture and its impact on transpiration reduction – must also be included in the transpiration calculation. More detailed information on this dual crop coefficient can be found in Allen et al (1998), Burt, et al (2002), and Walter et al (2000) but the basic concepts will be summarized in the following paragraphs from Burt, et al (2002).

> The basal crop coefficient (K_{cb}) is the fraction of reference evapotranspiration that will equal the potential transpiration of a certain plant plus a small component of evaporation from a dry soil surface. The K_{cb} value will vary with the growth stage of the plant; for an annual crop it typically has a value of 0.15 near planting, and reaches a maximum value of 0.9 - 1.2 or so at full cover. The product of ($K_{cb} \times ET_o$) equals the crop evapotranspiration under a well-watered condition with no stress and a dry soil surface, also referred to as crop basal evapotranspiration (ET_{cb}). These conditions are very rare in a field application. The K_{cb} has no irrigation management component or soil type component (it assumes perfect irrigation scheduling and a small water vapor evaporation component from the subsoil). Therefore, in concept it is transferable to anywhere in the world with minor adjustments. The minor adjustments are based on monthly average minimum relative humidity and wind speed (Allen et al, 1998).
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> For actual estimates of crop evapotranspiration (ET_c), the basal crop coefficient is adjusted based on the amount of water stress that occurs, and an additional computation accounts for wet soil surface evaporation. Most crops undergo some water stress throughout the growing period. Water stress occurs at a certain moisture depletion level. This level varies depending on the crop and its resistance to water stress. The dual crop coefficient method uses a crop stress coefficient (K_s) as a multiplier to reduce the potential transpiration because of the plant response to water stress. Therefore, the actual transpiration is [$K_s \times K_{cb}$] $\times ET_o$, minus a small amount of evaporation inherent in K_{cb}.
>
> The evaporation component of the crop coefficient is the evaporation coefficient (K_e). It is calculated based on soil type and the evaporable water in the upper region of the soil. The evaporable water in this upper region is determined using a soil water balance. The overall equation using the dual crop coefficient to calculate ET_c is:

$$\mathbf{ET_c = [(K_s \times K_{cb}) + K_e] \times ET_o} \text{ (Allen et al, 1998)}$$

In order to utilize the dual crop coefficient method to calculate crop evapotranspiration, a daily root zone soil water balance is needed. This model tracks soil moisture depletion, irrigation and precipitation events and past crop water usage to determine the current ET_c.

Irrigation Scheduling Program – Daily Water Balance

A spreadsheet irrigation scheduling program was developed for the Palmdale EMS site that tracks daily data on crop development, weather, ET_o, irrigation, etc. to accurately determine ET_c, as well as predict weekly irrigation demands for the following week. The irrigation scheduling program tracks each of the 27 center pivots at the EMS. Inputs include:

1. Planting and harvest dates
2. Weather data including ET_o, precipitation, temperature, and wind speed
3. Actual volume of effluent applied to each center pivot
4. Soil types
5. Pivot distribution uniformity
6. Crop type and crop specific inputs such as root zone depth, soil moisture depletion at the start of stress, crop height, etc.

On a weekly basis the spreadsheet program outputs the estimated volume needed to meet ET_c demands and refill the next week's soil profile for each pivot. In addition, the program tracks the amount of nitrogen applied to each pivot through the effluent.

Verification

With any model or irrigation scheduling program, verification is necessary to confirm that the program is functioning correctly. This requires field measurements and should be considered the most important part of the management process. The field verification ensures that the program/model is accurately tracking what is occurring in the field.

Soil moisture and vadose zone sensors have been installed throughout the EMS. At least one site is located in each pivot. Each site consists of 3-4 soil moisture sensors located at different depths in and below the root zone and a vadose zone monitor to analyze the amount of water percolating below the root zone. However, again, the location of the sensor may not be "representative". Therefore, the data recorded at the monitoring sites is not taken as "absolute". The data is used to ensure that the soil monitoring equipment is working, and is not necessarily used to make sure the measured soil moisture depletion values in the root zone match up exactly with the irrigation scheduling program.

In addition to soil moisture measurements, having personnel visit the center pivots daily to make qualitative observations is very important for a practical irrigation scheduling regime. The daily field visits also provide information on physical operations at the EMS.

Matching Supply and Demand

The components of the water and nitrogen balance have been discussed. The pieces must be put together in order to maximize effluent utilization and minimize deep percolation of nitrate. A major issue when using effluent for plant water requirements is that effluent supply is relatively constant throughout the year but plant water demands vary. **Figure 3** shows the relative plant demand by month versus the effluent supply (Note: The ET_o and effluent supply are in inches per month and million gallons per month (MGM), respectively).

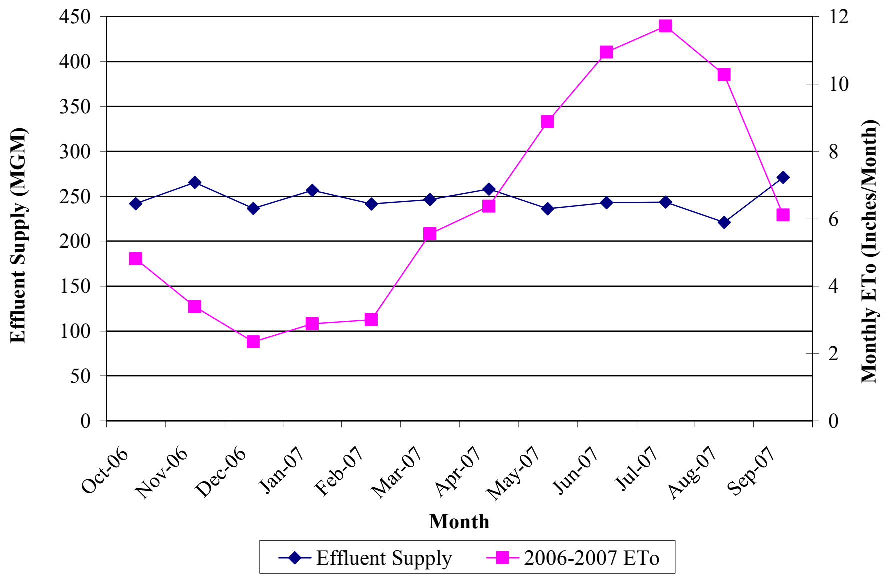


Figure 3. Average grass reference evapotranspiration (ET_o) compared to effluent supply over a recent year

Figure 3 shows that the effluent supply is relatively constant throughout the year, while the demand fluctuates. To overcome the supply and demand dilemma at the EMS, crop acreage is varied over the season. During the winter when ET_o is lowest, the entire 2,000-acre site is planted with crops (alfalfa and winter grain hay). During the summer when ET_o is highest, only the alfalfa is grown (approximately 900 acres) along with a small amount of sudangrass (approximately 30 acres). Even with this acreage reduction, the alfalfa is still under-irrigated to ensure that soil moisture is utilized and deep percolation is minimized. **Figure 4** shows the actual crop evapotranspiration (ET_c) compared to total effluent supply (both in million gallons per month (MGM)).

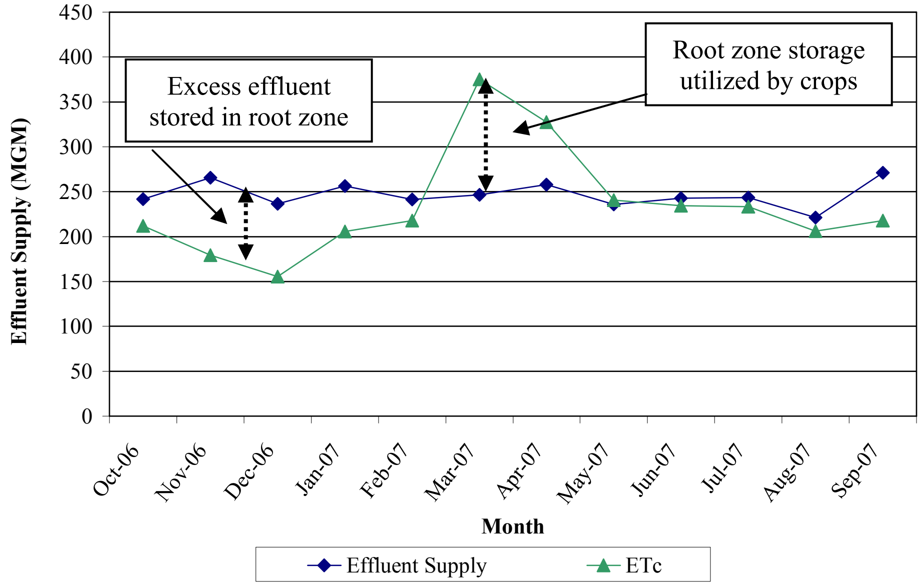


Figure 4. Actual ET of applied effluent compared to effluent supply

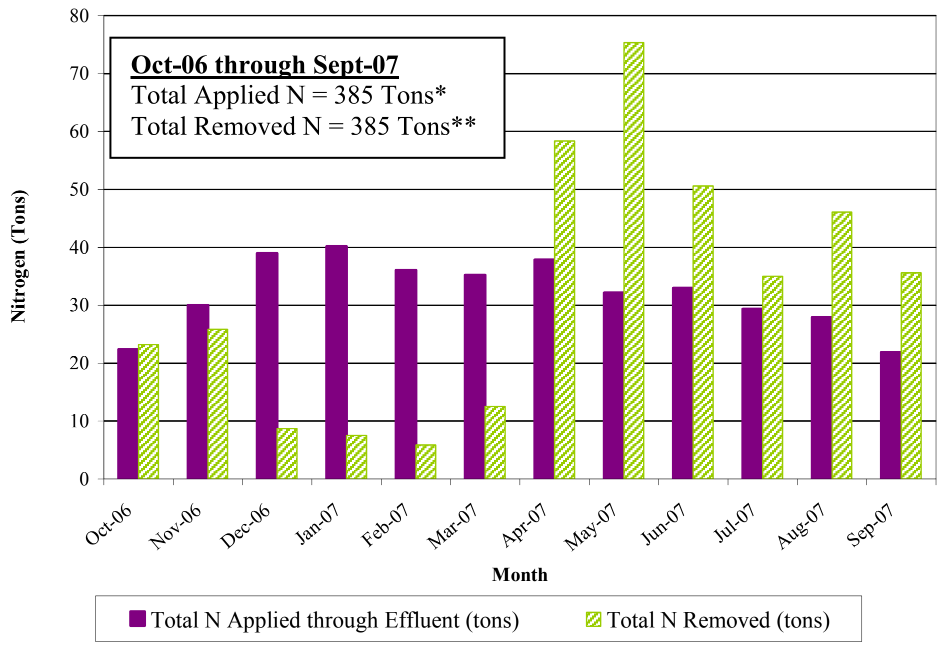
From **Figure 4**, a discrepancy still exists between effluent supply and crop demands even with crop acreage adjustments. During the fall and winter there is more effluent available than can be utilized by the crops. This is where the soil profile reservoir is fully utilized. By September the soil's available water reserves are fully utilized. The crops' water requirements are being met solely by applied water. As the water applications begin to outpace water utilization in October the root zone soil profile in each of the center pivots begins to refill, acting as a reservoir. This reservoir holds excess water from October through February. By March the crop water demands outpace applications and the soil reserves begin to deplete. Winter grain hay is harvested in April through May, decreasing the crop acreage and ET_c across the EMS, so that by summer the supply and demand match up.

The cropping strategy at the Palmdale EMS is a well choreographed plan that maximizes effluent utilization by minimizing water and nitrate loss through deep percolation. The cropping plan is created by November for the following year and lays out the basic strategy for the entire next season. This strategy accounts for each individual pivot, estimating the planting and harvest dates, daily irrigation applications, total nitrogen applied and removed, soil moisture content, etc. using a daily model with historical data. Then, using real-time data collected during the year, modifications are made to the plan to account for unforeseen events such as snow and ice damage to pivots.

Results and Conclusions

There are a number of items that must be considered when measuring success or failure in this type of field application. In most agricultural applications, crop yield is the major consideration in determining success along with some analysis of inputs, to ensure waste is minimized. However, at the EMS, yield is secondary to ensuring that nitrates do not leach below the root zone and effluent water use is maximized. Fortunately, yield, nitrogen utilization, and effluent utilization are all connected.

Meeting Regulatory Requirements
Figure 5 shows the nitrogen applied (does not include N fixation) and removed over the year. Nitrogen removed in **Figure 5** only includes volatilization, denitrification, and harvest (not leaching). Harvests typically occur from April through October, when the majority of nitrogen is removed from the EMS. Nitrogen is applied through irrigation. The variation in applied nitrogen is due to differing concentrations in the effluent.



* The total applied nitrogen does not include nitrogen fixed by alfalfa
**Total nitrogen removed does not included nitrogen leaching below the root zone

Figure 5. Nitrogen applied and removed over the year

Interestingly, the total nitrogen applied and removed from the EMS from October 2006 through September 2007 was equal. However, this is misleading because the N applied does not include nitrogen fixed by alfalfa and the N removed does not include nitrogen leached or percolated below the root zone.

Using the nitrogen balance equations (Methods 1 and 2) on a center pivot by center pivot case, the calculations indicate that approximately 75 tons of nitrogen either remains in the soil profile or percolates below the root zone from October 2006 – September 2007. It is inevitable that some nitrogen will be lost below the root zone in a productive irrigation application because distribution uniformity and irrigation timing cannot be perfect. With this understanding, the Regional Board has set a limit of tons of nitrogen that can be applied in excess of what is removed. Utilizing an intensive irrigation scheduling regime with proper monitoring, planning, and improved distribution uniformity (physical infrastructure) the actual excess nitrogen is within the prescribed limit.

Improving Past Performance
It can be difficult to compare current with past performance at any particular site when there have been modifications in operation or physical infrastructure. This is the case at the EMS. The site was expanded by over 1,000 acres in the last two years. Five of the center pivots have

been operating since the EMS started with the same operational rule of limiting effluent application to crop water demands plus reasonable losses from imperfect distribution uniformity and normal agronomic needs (such as seed germination irrigations and water applied to prevent wind erosion). However, only limited data on actual applications, soil moisture, and irrigation scheduling existed prior to ITRC's involvement at the EMS. The vadose zone monitoring devices that measure water percolating below the root zone did not pick up any deep percolation in 2006 or 2007 in the 5 pivots. One monitoring device did pick up a relatively significant volume in 2005 prior to ITRC's involvement. The accuracy and location of the equipment was questionable, however, so additional sensors have since been installed along with improved datalogging technology.

The only reliable data that is available prior to 2006 is harvested tonnage. However, the alfalfa crops on the 5 pivots in question were only 2-3 years old in 2004/2005. Crop tonnage is typically highest at 2-3 years of age, and declines in years 4-5 (2006/2007 for the 5 pivots shown in **Figure 6**). In addition, harvested tonnage does not necessarily relate to a reduction in nitrate leaching. Nevertheless, it is important to show that tonnage is approximately the same if not improved even though the crop is older.

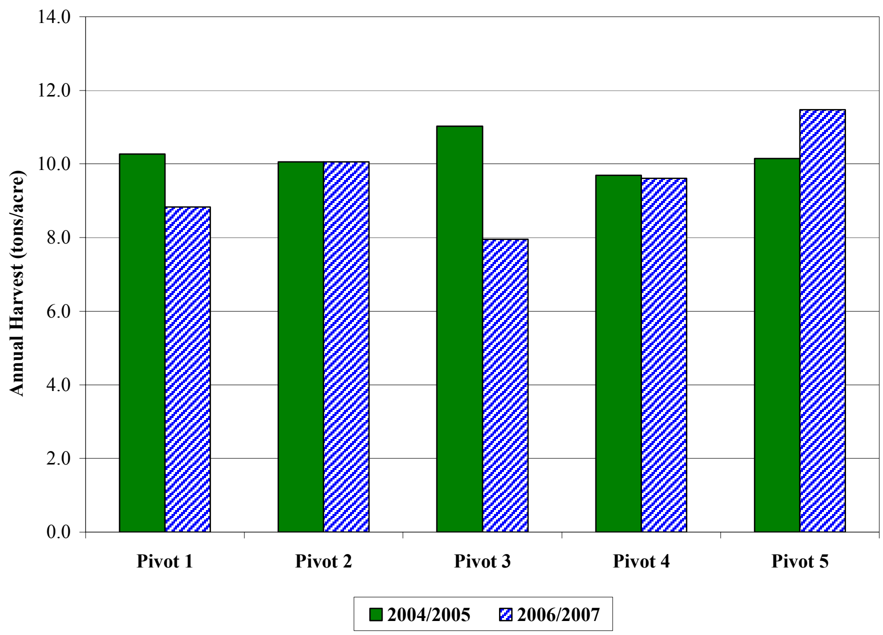


Figure 6. Harvest tonnage comparison from past to present (alfalfa)

The Districts have plans to install storage reservoirs as well as a tertiary treatment facility to decrease nitrate leaching even further. Additionally, the District's efforts have been so successful the Regional Board is in the process of lowering their limits based on new recommendations from the Districts and ITRC.

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