POTENTIAL OF SUBSURFACE DRIP IRRIGATION FOR MANAGEMENT OF NITRATE IN WASTEWATER

C.J. Phene* and R. Ruskin**

ABSTRACT

Annual increases of food demand forecasts for various regions of the world range from 2.3% (East and South Asia) to 3.8% (West Asia and North Africa). Even when taking into account the potential production of rain-fed agriculture, the irrigated agricultural production sector will need to increase its productivity by 3 to 4% per annum. Secondary and tertiary treated domestic wastewaters (WW) are being used more and more for irrigation of field crops, landscape, groundwater recharge and other applications. However, the use of treated WW for irrigation is subject to major concerns because of the potential nitrate contamination of domestic water supplies possibly resulting in the occurrence of methemoglobinemia. In California, only 18% of the 5 billion cubic meters of generated WW is treated and returned to the state’s fresh water system for incidental uses but only about 7% of it is used intentionally. The Water Management Research Laboratory (USDA-ARS-Fresno) developed a practical water and fertilizer efficient irrigation and management method which minimizes and sometimes even eliminates the downward movement of soluble nitrate-N below the root zone of field crops. The method known as deep high frequency subsurface drip irrigation (SDI) achieved minimum leaching when four conditions were satisfied: (1) irrigation events are short and frequent and designed to replace crop water uptake as closely as possible (no leaching fraction); (2) nitrogen is applied with the water through the SDI system at a rate equivalent to the uptake rate of the crop less the amount mineralized from the soil; (3) the crop is deep rooted; and (4) the shallow water table is at least 2.0 m from the soil surface. Results obtained for a ten year period with irrigated field crops demonstrate the potential of the SDI method for minimizing non-point source agricultural pollution with NO\textsubscript{3}-N. The SDI method also shows some unique and economical potential for safely irrigating field crops with treated WW. In addition to the controlled movement of NO\textsubscript{3}-N to the ground water, the mere fact that the treated WW does not come to the soil surface adds another safety dimension to the handling of a potentially hazardous material. In locations where year around cropping is possible, continuous disposal could be carried out without requiring major storage facilities. However, during the winter months when evapotranspiration (ET) is low, some reservoir might be required to store the excess WW not evapotranspired by the crop. The objectives of this paper are to present and discuss the design and operation of SDI systems, their physical characteristics, and research results defining soil water, nitrate-N and deep rootzone profiles obtained when deep SDI systems are used. The authors will relate how this method can be adapted for irrigation with treated WW.

Keywords: Reuse, Water use, Leaching, Treated Water

INTRODUCTION

Annual increases of food demand forecasts for various regions range from 2.3% (East and South Asia) to 3.8% (West Asia and North Africa). Even when taking into account the

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potential production of rain-fed agriculture, the irrigated agricultural production sector will need to increase its productivity by 3 to 4% per annum. Presently, in view of the fact that 20-30 Mha of existing irrigated agriculture is facing severe salinity problems, the 3-4% targeted increase will be an almost impossible goal to achieve without significant increases in water conservation, including steps such as reuse of agricultural and urban effluents (Hennessy, 1993).

Secondary and tertiary treated domestic wastewaters (WW) are being used more and more for irrigation of field crops, landscape, groundwater recharge and other applications (Nellor et al., 1985; Brown, 1987; Burau et al., 1987 and Kirkpatrick and Asano, 1986). Secondary treated WW has even been considered for irrigation of raw-eaten vegetable crops (Kirkpatrick and Asano, 1986; Sheikh et al., 1986). However, the use of treated WW for irrigation is subject to major concerns because of the possible nitrate contamination of domestic water supplies and potential occurrence of methemoglobinemia (blue baby disease), as well as health hazards from the pathogens in WW (Broadbent and Reisenauer, 1990).

In California, only 18% of the 5 billion cubic meters of generated WW is treated and returned to the state’s fresh water system for incidental uses but only about 7% of it is used intentionally. Although legal and institutional rights to the reclaimed water are a major regulatory obstacle to its use, health, safety, economics and environmental concerns also play important roles in limiting its widespread uses (Pettygrove et al., 1990).

Page and Chang (1990) concluded that when WW are used for irrigation of crops, the concentration of trace elements is not high enough to cause any short-term acute harmful effects, but long-term accumulation (approximately 100 years) in soil could exceed proposed limits for soil deposition of trace elements. Since the concentration of trace elements varies significantly depending on the source, case by case evaluation should be conducted.

Wastewater usually contains three major forms of N: (1) Ammonium; (2) Organic N; and (3) Nitrate/nitrite. Ammonium (NH$_4^+$) represents the principal form of N in WW (5-40 mg N/L) but in most soil containing significant clay, some NH$_4^+$ can be either fixed by clay particles or temporarily adsorbed by negatively-charged clay and organic colloids. Organic N is readily converted to NH$_4^+$ by the mineralization transformation process resulting from aerobic and anaerobic bacteria activity. The two-step nitrification process transforms NH$_4^+$ to nitrite-N and then to nitrate-N, involving respectively Nitrosomonas and Nitrobacter bacteria. Although these bacteria are present in most soils, their population may be quite low in subsoils and dry sandy soils and their activity may be restricted if the soil temperatures are low (Broadbent and Reisenauer, 1990).

The President’s Water Quality Initiative (WQI) was initiated in 1989 in response to widespread concern that agricultural activities contribute to the contamination of the Nation’s ground waters (GW). The WQI goal is to relate agricultural activities to GW quality and to develop and implement farm management strategies that protect GW. The USDA was directed to achieve this goal and the staff of the Water Management Research Laboratory (USDA-ARS-Fresno) developed a highly water and fertilizer efficient irrigation and management method which minimized and sometimes even eliminated the downward movement of soluble nitrate-N below the root zone of field crops. The method known as deep (0.45 m below the soil surface or deeper) high frequency subsurface drip irrigation (SDI) can achieve minimum leaching if four conditions are satisfied: (1) irrigation events are short and frequent and designed to replace crop water uptake as closely as possible (no leaching fraction); (2) Nitrogen is applied with the water through the SDI system at a rate equivalent to the uptake rate of the crop less the amount mineralized from the soil; (3) the
crop is deep rooted; and (4) the shallow water table is at least 2.0 m from the soil surface. Hence, an SDI system should be ideal for applying treated WW with minimal potential leaching of nitrate-N, because the nitrification process will be minimized and some NH₄⁺ molecules will be either fixed or adsorbed by the soil and mostly taken up by the deep roots.

The objectives of this paper are to present and discuss the design and operation of SDI systems, their physical characteristics, and research results defining soil water, nitrate-N and deep root zone profiles obtained when deep SDI systems are used. The authors will relate how this method can be adapted for irrigation with treated WW.

MATERIALS AND METHODS

Research Applications of SDI for Minimizing Drainage and Nitrate Leaching Under intensive Field Cropping Systems.

In 1984, a SDI system was installed by the USDA-ARS-WMRL at Five Points, CA (University of California, Westside Field Station). The soil is a Panoche clay loam (Typic Torriorthents) with excellent water retention and a depth exceeding 2 m. This SDI system has been in use ever since and is the system used in all the research reported herein.

The experimental design is a randomized block, consisting of three irrigation treatments, replicated four times. Each plot contains 10 beds, spaced 1.63 m from center to center and 91 m long. One treatment consisted of SDI laterals installed early in 1984 in one of the three field treatments and in a lysimeter and the other two treatments consisted of surface drip at high frequency (HFDI) and at low frequency (LFDI). These laterals were installed yearly after the crop was germinated. SDI laterals were trenched at the center of each SDI bed and at a depth of 0.45 m from the soil surface. The laterals are spaced 1.63 m apart and consist of in-line turbulent flow emitters (Agrifirm), spaced 1.0 m apart along the laterals and with a discharge rate of 4 L/h (Davis et al., 1985). A large precision weighing lysimeter measured the crop evapotranspiration (ETc) and was used in a feedback mode to schedule irrigation automatically in the SDI treatments after 1 mm of ETc had occurred (Phene et al., 1989).

Each year at planting, N and P fertilizer (11-48-0) was applied at a rate of 112 kg/ha, directly below the seeds. All remaining fertilizers were injected daily through the SDI and surface drip systems with the injection rate of N, P, and K designed to match the crop uptake of each nutrient. Weekly tissue analyses were used to adjust the injection rates to maintain a sufficient nutrient level for each nutrient (Phene, 1993).

During the ten year period from 1984 to 1993, this SDI system was used intensively to grow many field crops, often achieving extremely high water use efficiency. The same experimental design was used until the end of the 1990 cropping season. Basic ET, precipitation, irrigation, drainage and water use efficiency data are shown in Table 1. In 1991, the field was fallow; in 1992, the two surface drip irrigated treatments (HFDI and LFDI) were converted to two SDI treatments, installed at 0.30 m and 0.60 m depths and the original SDI system installed at 0.45 m in 1984 was maintained as the original treatment. Wheat was grown in 1992 and cotton in 1993.
Table 1. Yearly values (12 months) of reference and crop evapotranspiration, precipitation, irrigation, drainage and water use efficiency (WUE) for several crops irrigated by subsurface drip irrigation from 1984 to 1990, at Five Points, California.

<table>
<thead>
<tr>
<th>CROP/YEAR</th>
<th>ET₀</th>
<th>Crop ETₑ &amp; Soil E</th>
<th>Precipitation</th>
<th>Irrigation Application</th>
<th>Drainage</th>
<th>WUE*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomato (1984)</td>
<td>1,823</td>
<td>959</td>
<td>104</td>
<td>692</td>
<td>0**</td>
<td>2.20</td>
</tr>
<tr>
<td>Tomato (1985)</td>
<td>1,720</td>
<td>855</td>
<td>127</td>
<td>792</td>
<td>59</td>
<td>2.41</td>
</tr>
<tr>
<td>Cantaloupe (1986)</td>
<td>1,701</td>
<td>863</td>
<td>167</td>
<td>552</td>
<td>90</td>
<td>1.81</td>
</tr>
<tr>
<td>Tomato (1987)</td>
<td>1,657</td>
<td>793</td>
<td>187</td>
<td>658</td>
<td>36</td>
<td>3.88</td>
</tr>
<tr>
<td>Cotton (1988)</td>
<td>1,583</td>
<td>979</td>
<td>205</td>
<td>694</td>
<td>83</td>
<td>3.13</td>
</tr>
<tr>
<td>Sweet Corn (1989)</td>
<td>1,514</td>
<td>693</td>
<td>86</td>
<td>667</td>
<td>2</td>
<td>2.92</td>
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<tr>
<td>Tomato (1990)</td>
<td>1,618</td>
<td>875</td>
<td>145</td>
<td>773</td>
<td>38</td>
<td>2.41</td>
</tr>
<tr>
<td>MEANS (1984-1990)</td>
<td>1,659</td>
<td>860</td>
<td>146</td>
<td>689</td>
<td>44</td>
<td>2.68</td>
</tr>
</tbody>
</table>

* WUE defined as total above-ground dry matter yield + irrigation water applied.
** In 1984 the initial water content of the lysimeter was relatively low due to drying down by the previous crop.

A. General SDI design characteristics and operation criteria.

The design and successful operation of subsurface drip irrigation systems evolved over the years but differ only slightly from that of standard drip systems except for three important criteria: (1) Vacuum relief valves must be installed at several locations, principally at the highest elevation points of the system; (2) SDI systems require frequent flushing of the mains, submains and laterals, especially during their first 6 months of operation. Installation of a buried flushing submain can be used to facilitate lateral flushing and; (3) Because the root systems of crops irrigated by SDI systems are deeper, fertility management becomes more critical since the root zone will extend into soil lacking many nutrients. Figure 1 shows the basic configuration of a SDI system lateral and its connection to the submain and flushing submain (Phene, 1993).

The SDI systems also need to be irrigated very frequently, but that is also true of surface drip systems. However, for SDI systems which are not using trifluralin-impregnated emitters, the frequent irrigation with simultaneous continuous injection of phosphoric acid and yearly injection of fumigant (sodium Metham) has been shown to be necessary to prevent emitter plugging and root intrusion of field crops for up to ten years. Perennial crops should use the trifluralin-impregnated emitters since fumigant injection is not always possible.

B. Unique Physical Characteristics of SDI Systems.

Three physical characteristics, unique to SDI, contribute to the advantages of this method and to minimizing nitrate-N leaching: (1) Reduced evaporation component of ETₑ (Phene et al., 1993b); (2) Larger wetted soil volume and surface area than surface drip; and (3) Deeper crop rooting patterns than surface drip. For the purpose of treated WW reuse, characteristics 2 and 3 are extremely important and therefore, they will be addressed here.
Fig. 1. Basic configuration of a SDI system lateral and its connection into the submain and flushing submain.

HEMISPHERICAL VERSUS SPHERICAL WETTING PATTERNS

<table>
<thead>
<tr>
<th></th>
<th>DI</th>
<th>SDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADIUS</td>
<td>0.40 m</td>
<td>0.36 m</td>
</tr>
<tr>
<td>AREA</td>
<td>1.005 m²</td>
<td>1.629 m²</td>
</tr>
<tr>
<td>VOLUME</td>
<td>0.134 m³</td>
<td>0.195 m³</td>
</tr>
</tbody>
</table>

Fig. 2. Differences in the geometrical characteristics of hemispherical and spherical wetting patterns of DI and SDI, respectively.
1. Large Wetted Soil Volume

One of the most obvious physical advantages of SDI over surface drip (DI) is the wetted soil pattern generated in the soil profile (Fig. 2). Phene et al. (1989, 1990), Ben-Asher and Phene (1993), and Phene (1993), have shown that capillarity will pull water radially from the source and therefore for a given discharge rate of water, (1) the spherical volume of a wetted clay loam soil is approximately 46% larger for the SDI system than the hemispherical volume wetted with a DI system, (2) the corresponding wetted surface area available for root uptake is 62% larger in the SDI system than in the DI system (excluding the soil surface in the surface drip pattern), and (3) the shorter wetted radius in the SDI system will allow closer emitter spacing than in the DI system, resulting in improved wetted uniformity.

2. Deep Rooting Pattern

Hybrid sweet corn (Zea mays L., cv. Supersweet Jubilee) was grown during 1989 in the field plots described above. Figure 3 shows the covariance curves plotted to show differences in root length densities (RLD = the root length per unit volume of dry soil) between high frequency DI (HFDI) and SDI (RLD_{HFDI} - RLD_{SDI}) (Phene et al., 1990). The solid line represents the treatment differences in RLD and the dashed lines represent the 95% confidence band about the treatment differences. From the soil surface to a depth of 0.2 m the RLD of the sweet corn grown under HFDI was greater than that in the SDI treatments. However, the RLD of sweet corn grown with the SDI system was greater than that grown under the HFDI treatment from a depth of approximately 0.2 m below the soil surface to nearly 1.9 m depth. Similar rooting patterns have been characterized for cotton and tomato and in general it was found that the maximum RLD occurs at the depth of the water source, at least down to 0.60 m.

C. Minimizing Deep Percolation and Nitrate-Nitrogen Leaching

In 1987, Phene et al. (1989) used the weighing lysimeter to measure evapotranspiration of a SDI irrigated tomato crop. In this experiment, the water supply rate (I) was equal to the sum of soil evaporation (E), plant transpiration (T) and deep percolation (D) less precipitation (P). Water was applied as often as 1.0 mm/h as measured by the mass change of the weighing lysimeter. In this study, a shallow water table was maintained at a depth of two meters. This caused a slight upward hydraulic gradient from the water table. The soil matric potential (SMP) of the Panoche clay loam soil was measured hourly at depths of 0.15, 0.30, 0.70, 1.00, 1.55 and 2.00 m and the crop lysimeter was irrigated by an SDI system with the drip lateral installed 0.45 m deep. Figure 4 shows the hourly SMP for a 24-hour period in the lysimeter with a mature tomato crop. Irrigations (1.0 mm/h) are shown by the arrows located on the horizontal time axis. Figure 5 shows the calculated mean daily SMP from hourly measurements for a period of 30 days. These data indicate that the SDI system maintained a nearly constant daily and seasonal SMP profile and a net upward hydraulic gradient (\(\Delta H/\Delta Z\)) where \(\Delta H\) is the hydraulic head and \(\Delta Z\) is the vertical distance between measurement points.

Figure 6 shows the SMP profile and the direction of \(\Delta H/\Delta Z\) for day 195 of 1987. These data indicate that except directly below the drip lateral, between soil depths of 0.45 and 0.70 m, \(\Delta H/\Delta Z\) is upward everywhere else. Therefore the net flux of water and salts is upward and deep percolation losses can either be prevented or controlled. By using this high frequency SDI management approach with salt-tolerant crops we can also force the plant to utilize a significant volume of water from the water table and thus help temporarily and locally control the water table level without drainage outflow.
Fig. 3. Distribution of root length density differences (HFDI-SDD) in cm/g of dry soil for sweet corn. The solid line represents the treatment difference and the dashed lines are the 95% confidence intervals.

Fig. 4. Daily soil matric potentials at 0.15, 0.30, 0.70, 1.00, 1.55 and 2.00 m depths, on day 207 of 1987 for a tomato crop growing in a lysimeter irrigated with a single drip line at 0.45 m depth, in the presence of a water table deeper than 2.00 m depth. Small arrows on x-axis indicate 1.0 mm irrigation through the subsurface drip irrigation system (after Phene et al., 1989).
Fig. 5. Mean daily soil matric potentials at 0.15, 0.30, 0.70, 1.00, 1.55 and 2.00 m depths, from day 195 to day 225 of 1987 during the maturation phase of a tomato crop growing in a lysimeter irrigated with a single drip line at 0.45 m depth, in the presence of a water table deeper than 2.00 m depth (after Phene et al., 1989).

Fig. 6. Soil matric potential and direction of the soil hydraulic gradient in the lysimeter, irrigated with a single drip line at 0.45 m depth and in the presence of a water table deeper than 2.00 m depth for day 195 of 1987 (after Phene et al., 1989)
Figure 7 shows the soil NO$_3$-N concentration profile, before and after a cotton crop in 1988. These data indicate that deep rooted crops, such as cotton, tomato and corn, can actually extract most of the NO$_3$-N from the deep soil profile during the season (Phene, et al., 1990). In 1988, most of the drainage from the lysimeter occurred early in the season, following the unusually high rainfall for this location (205.7 mm, the long term mean is 150 mm), and before the application of NO$_3$-N to the irrigation water. At the end of the season, a large increase in NO$_3$-N concentration also occurred near the soil surface resulting from the extremely large amount of dry matter which decomposed in the top 0.30 m (Phene, 1993). Calculations of N uptake by the crop indicated that approximately 80 kg/ha of N was taken up from the soil in addition to the 250 kg/ha applied N.

A method to estimate the leaching of NO$_3$-N has been described by Pratt et al., (1978). This method assumes that: (1) the quantity of chloride (Cl$^-$) added in excess of removal in harvested crops is leached from the root zone in the percolating water, (2) Cl$^-$ does not react with the soil to impede its movement with the percolating water, and (3) the soil does not release Cl$^-$ by weathering processes. In other words, the Cl$^-$ (as a conservative ion, when adjusted for crop removal) is concentrated in the percolating water in direct proportion to the quantity of water removed in the evapotranspiration process. It can be used to calculate a leaching fraction, i.e., the fraction of the total water intake that leaches beyond the root zone.

This method was applied to NO$_3$-N and Cl$^-$ samples obtained from this field in 1988 to corroborate our previous NO$_3$-N analysis. The NO$_3$-N/Cl$^-$ are plotted with depth in Fig. 8 for the spring and fall NO$_3$-N measurements shown in Fig. 7. The magnitude and confidence intervals for these measurements below 1.33 m are extremely small and not significantly different between spring and fall measurements. Above 1.33 m, the large increase in the ratio in the spring resulted from surface accumulated organic matter from the previous crop which decomposed and was moved downward by winter precipitation. However, by the end of the season, most of the NO$_3$-N has been taken up by the crop except near the soil surface which is maintained dry with the SDI method.

The research referred to in this paper was done on Panoche Clay Loam soils. Other research not discussed here and commercial experiences on lighter texture soil (such as Hanford Fine Sandy soil) indicate that with closer emitter and lateral spacings, similar results can be achieved.

**D. Economics and Capital Costs**

Phene et al. (1993a) have discussed the economics of SDI, using results with cotton from a five year demonstration project, funded by the California Department of Water Resources (DWR) and from several large commercial systems. The results of the DWR project demonstrated that even for cotton (a marginal crop in terms of economics), SDI was economically feasible and that it returned an average net income of $660.00/ha/year, $72.00 and $156.00 more than conventional furrow and improved furrow irrigation, respectively. Total permanent SDI installation costs (including in-field filtration) range between $2,000 and $4,000 per hectare. A typical SDI system is also expected to last at least ten years when managed properly. In addition to the precise control of nitrate movement, SDI also provides a substantial reduction of potential health risks, both to the grower and to the consumer of edible crops. With SDI, it is practical to use filtered secondary treated water (Oron et al., 1991). With sophisticated real time monitoring and control of the field equipment, it may even be practical to use filtered primary treated effluent. Thus, the savings in capital cost of water treatment plants may be several times the cost of the sophisticated SDI system.
Fig. 7. Nitrate-Nitrogen concentrations in a deep Panoche clay loam soil, from 0-2.70 m depth before planting of a cotton crop in March 1988 and following the harvest in November 1988, when irrigation/fertigation was done with a SDI system permanently installed at 0.45 m depth.

Fig. 8. Relationship between nitrate-nitrogen/chloride ratio in the soil saturation extract and soil depth for a Panoche clay loam profile irrigated and fertilized with a SDI system for the NO$_3$-N measurements shown in Fig. 7.
Geoflow and Woodward-Clyde International, Asia-Pacific Office have developed a technique to use primary treated water (Geoflow, 1994) (see Fig. 9). The whole system is monitored and controlled by a Programmable Logic Controller (PLC) with real time communication to the engineer's office. When a pressure increase is sensed, the SDI system is automatically flushed by bypassing the pressure regulator. In the event of any flow decrease due to bacterial slime, fresh water and chlorine are automatically injected into the system, allowed to remain in the line for 40 minutes of contact time and then flushed out with either fresh water or WW and acid. A 100 ha eucalyptus field has been planned as a demonstration system and it is expected that installation will be finished and operation will begin before the end of this year.

Fig. 9. Anaerobic wastewater irrigation schematic.

CONCLUSION

These combined results demonstrate the potential of the SDI method for minimizing non-point source agricultural pollution with NO$_3$-N. Although drainage outflow can be reduced greatly and the soil EC$_e$ in the root zone is tolerable for most field crops, this practice may not complete eliminate the need for drainage to sustain the long term salt balance of irrigated agriculture in arid regions (van Schilfgaarde, 1990).

The SDI method shows some unique and economical potential for safely irrigating field crops with treated WW. In addition to the controlled movement of NO$_3$-N to the ground water, the mere fact that the treated WW does not come to the soil surface adds another safety dimension to the handling of a potentially hazardous material. In locations where year around cropping is possible, continuous disposal could be carried out without requiring major storage facilities. However, during the winter months when ET is low, some reservoir might
be required to store the excess WW not evapotranspired by the crop. Because of the relatively low N concentration, this disposal method could be used with a deep rooted crop such as alfalfa, using a SDI system installed at 0.60 m or deeper. When the active root system of alfalfa is 0.5 m deep, the nitrogen fixation process may be impaired and the frequent injection of N is needed to produce good quality alfalfa and high yields. Recent USDA-ARS-WMRL research results with SDI for alfalfa have shown that this method is indeed feasible, conservative and sustainable. Since about 100,000 ha of alfalfa is grown year around in the Imperial Valley of California, the potential for adopting this method to process effluents from many surrounding cities in Southern California should be investigated.

ACKNOWLEDGEMENT

The authors acknowledge that the research described therein was performed by the staff of the USDA-ARS, Water Management Research Laboratory, Fresno, California while the senior author was the Research Leader of the Laboratory. This research was performed at the University of California’s West Side Field Station in cooperation with their support staff. The authors thank both staffs for their outstanding support and cooperation during this long-term project.

REFERENCES


**Figure 9.** Anaerobic wastewater irrigation schematic
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HEMISPHERICAL VERSUS SPHERICAL WETTING PATTERNS

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<tr>
<td>RADIUS</td>
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<td>0.36 m</td>
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<tr>
<td>AREA</td>
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<td>VOLUME</td>
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<td>+46</td>
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