A NEW DRAINPIPE–ENVELOPE CONCEPT FOR SUBSURFACE DRAINAGE SYSTEMS IN IRRIGATED AGRICULTURE†

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ABSTRACT

On irrigated lands, drainpipe performance is often below standard due to clogging, siltation and root growth inside the pipe. To tackle these problems, an innovative pipe–envelope concept was tested on a 50 ha pilot area in Harran, Turkey, in 2015 and 2016. The new concept, HYDROLUIS, consists of a corrugated inner pipe with three rows of perforations at the top and an unperforated outer pipe that covers about 2/3 of the inner pipe leaving only the unperforated bottom part of the inner pipe in contact with the soil. The main advantages of the new concept are that it works for a wide range of soil textures and there is better protection against root growth inside the pipe. The new concept was compared with a geotextile envelope, a gravel envelope and a control with no envelope. The HYDROLUIS and gravel envelopes had a significantly lower entrance resistance compared to the geotextile, the best drain performance and no signs of sedimentation nor of root growth inside the pipe. The production costs of the HYDROLUIS envelope are comparable to those of pre-wrapped synthetic envelopes and considerably lower than gravel envelopes. It can be concluded that the HYDROLUIS envelope is a promising alternative for sand/gravel or synthetic envelopes in irrigated lands. © 2018 The Authors. Irrigation and Drainage published by John Wiley & Sons Ltd on behalf of International Commission for Irrigation and Drainage

KEY WORDS: drain performance; envelope material; entrance resistance; root growth; subsurface drainage

RÉSUMÉ

Dans les terres irriguées, les performances des tuyaux de drainage sont souvent inférieures à la norme en raison du colmatage, de l’envasement et de la croissance des racines à l’intérieur du tuyau. Pour résoudre ces problèmes, un concept innovant d’enveloppe de tuyaux a été testé dans une zone pilote de 50 ha à Harran, en Turquie, en 2015 et 2016. Le nouveau concept, HYDROLUIS, se compose d’un tube intérieur ondulé avec trois rangées de perforations au sommet et un tuyau extérieur non perforé qui couvre environ 2/3 du tuyau intérieur ne laissant que la partie inférieure non perforée du tuyau intérieur en contact avec le sol. Les principaux avantages du nouveau concept sont qu’il fonctionne pour une large gamme de textures de sols et qu’il existe une meilleure protection contre la croissance des racines à l’intérieur du tuyau. Le nouveau concept a été comparé à une enveloppe géotextile, une enveloppe de gravier et un contrôle sans enveloppe. Les enveloppes HYDROLUIS et gravier ont une résistance d’entrée nettement inférieure à celle du géotextile, la meilleure performance de drain et aucun signe de croissance de la racine. Les coûts de production de l’enveloppe HYDROLUIS sont comparables à ceux des enveloppes synthétiques pré-enroulées et considérablement inférieurs aux enveloppes de gravier. On peut conclure que l’enveloppe HYDROLUIS est une bonne alternative pour les enveloppes de sable/gravier ou synthétiques dans les terres irriguées. © 2018 The Authors. Irrigation and Drainage published by John Wiley & Sons Ltd on behalf of International Commission for Irrigation and Drainage

MOTS CLÉS: performance de drain; matériel d’enveloppe; résistance d’entrée; croissance des racines; drainage souterrain

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INTRODUCTION

The life of subsurface drainage systems can be hundreds of years if no blockage, deformation and siltation occur (Stuvt et al., 2005; Jahn et al., 2006). Blockage of the pipes generally occurs due to sanding, siltation, chemical and biological settlement, penetration of plant roots into the pipe, accumulation of compressed filling soil in drainage trenches (in very wet environments) or improper installation of individual pipes (Eggelsmann, 1987). A common practice to prevent penetration of plant roots into the pipes is to increase installation depth. To prevent poor drain-line performance from other causes of blockage, drain envelopes are generally used. A drain envelope has three functions (Ritzema et al., 2006):

- **Filter function**: to prevent or restrict soil particles from entering the pipe where they may settle and eventually clog the pipe;
- **Hydraulic function**: to create good permeability around the pipe and thus reduce entrance resistance;
- **Bedding function**: to provide all-round support to the pipe in order to prevent damage and deformation due to the soil load. Note that large-diameter plastic pipes are embedded in gravel especially for this purpose.

A wide variety of materials is used as envelopes for drainpipes, ranging from organic and mineral materials, to synthetic material and mineral fibres (Cavelaars et al., 2006). Organic material is mostly fibrous, and includes peat—the classical material used in western Europe—coconut fibre, and various organic waste products such as straw, chaff, heather and sawdust. Mineral materials are mostly used in a granular form; they may be gravel, slag of various kinds (industrial waste products) or fired clay granules. Synthetic materials may be in a granular (e.g. polystyrene) or in a fibrous form (e.g. nylon, acryl and polypropylene). Glass fibre, glass wool and rock wool, which all are mineral fibres, are also used (Vlotman et al., 2001).

To prevent entry of sediments into drainpipes, pipes are wrapped in envelopes selected according to the characteristics of the soil in which they will be installed. For example, in soils that are problematic in terms of siltation, the purpose of the envelope is to prevent penetration of soil particles into the drainpipe (Zaslavsky, 1978). The first group of problem soils are those high in silt and fine sand and low in clay content (Cavelaars et al., 2006). Such soils have insufficient clay particles to be cohesive enough to maintain stable structural elements. At the same time, the soil particles are not big enough to form a stable skeleton over the inlet openings of the pipe or over the pores of the envelope material. This leads to entry of soil particles into the drainpipe. A second group of problem soils are those with structureless conditions, for example unripe clay soils. These soils have a very low permeability, leading to high inflow resistance. Increasing the size of the perforations and consequently the total area of holes in the plastic drainpipes decreases the entrance resistance (Cavelaars, 1965). However, this can increase the risk of soil particles entering the pipes. Therefore, envelope material wrapped around the pipe to prevent sediment penetration into the pipe must also have characteristics that do not increase entrance resistance (Wesseling and Homma, 1967). In an experiment conducted in a horizontal sand tank with a fine sandy loam soil, (Robert et al., 1987), who tested different envelope options, achieved the highest flow rate and lowest siltation in pipes wrapped with geotextiles.

The criteria for the ‘filter’ and ‘hydraulic’ functions of envelopes are somewhat conflicting, as the ‘filter’ function requires a dense envelope with small pore spaces and the ‘hydraulic’ function requires an open envelope with large pore spaces. Apart from these conflicting ‘filter’ and ‘hydraulic’ functions, the formulation of functional criteria for envelopes is complicated by a dependence on soil characteristics, mainly soil texture, and installation conditions (Stuvt and Dierickx, 2006; Stuvt and Willardson, 1999). Vlotman et al. (2001) reviewed the simultaneous development of pipe–envelope theory and practical experience in Europe and North America. Traditionally, the envelope around the drainpipe consisted of the best-suited locally available materials like stones, gravel or straw. In arid areas, the technique of using gravel envelopes was further developed such that effective gravel envelopes can be designed for most soils (United States Bureau of Reclamation, 1978). In practice, gravel envelopes are often expensive due to the high transport costs, while their installation is cumbersome and error-prone, and requires almost perfect logistic management during installation to be effective (Ritzema et al., 2006). Moreover, gravel cannot be used when installation is carried out with trenchless drainage machines. In the 1960s and 1970s much research was done to develop pre-wrapped envelopes of synthetic material, including the development of specialized machinery to pre-wrap sheet and loose-fibre envelopes around the drainpipes. Pre-wrapping is done in the factory and not in the field to guarantee a better quality and easier quality control (Nijland et al., 2005). Nowadays, pre-wrapped synthetic envelopes are used almost everywhere in Europe, in the Midwest and eastern states of the United States, in the Middle East, the Indian subcontinent and east Asia. However, only limited research has been done on locally made synthetic envelopes for subsurface drainage in irrigated lands (El-Sadany Salem et al., 1995; Kumbhare and Ritzema, 2000). Since the specifications of envelopes are very soil-specific and soils vary widely, the specifications and effectiveness of envelopes have to be proven in field trials in the areas where they are to be applied (Vlotman et al., 2001). This is a cumbersome and time-consuming activity; see for example Ritzema et al. (2008) for the need for an envelope material for various soil conditions in India.
Soils with a clay content >60% generally do not require a filtering drainage envelope, but in arid regions soils are generally less stable than in humid areas, so clay content alone is not a good indicator of soil strength and stability (Vlotman et al., 2001). Thus, although there are many studies and publications that suggest that there is no need for envelopes in mature, structurally developed, stable soils that contain more than 60% clay (Vlotman, 1998), in Turkey drainpipes in these type of soils are generally equipped with envelopes (Bahçeci et al., 2001). This is done because experience has shown that even in these soil conditions, drainage is more effective when a pipe envelope is used. In particular, it appears that gravel materials improve the hydraulic conditions around the pipe. Under these conditions, a gravel envelope obtained from natural sand–gravel pits gives the best performance. The oldest drainage system equipped with such a sand–gravel envelope was built in the Çukurova region in the 1970s. Until now, however, there has been no comprehensive study of its performance, but farmers’ complaints have increased and they have requested cleaning and renovation. In the Aegean, Manisa, Denizli-Sarayköy and Konya regions, subsurface drainage systems equipped with sand–gravel envelopes were built in the 1980s and 1990s. At the start of the South-eastern Anatolia Project, a sand–gravel envelope was also prescribed for the Harran Plain. These sand–gravel envelopes are, however, very expensive and often the particle-size distribution of the natural sand gravels does not match the design specifications. Thus, more recently geotextiles have been used, which has been effective for hydraulic function but has led to the twin problem of clogging and root penetration. The main reason is probably that synthetic envelopes cannot be easily adjusted to local conditions and that only one type (PP450) is used.

To overcome the twin problem of clogging and root penetration, a new concept, the HYDROLUIS pipe–envelope system, has been developed (https://www.hydroluis.net/hydroluis). The new design concept aims to prevent penetration of plant roots and soil particles into the drainpipe by creating either an air- or water-lock. It consists of a corrugated inner pipe with three rows of perforations at the top and an unperforated outer pipe that covers about 2/3 of the inner pipe, leaving only the unperforated bottom part of the inner pipe in contact with the soil (Figure 1).

The geometry of the HYDROLUIS pipe–envelope combination prevents or reduces deformation of the pipes by providing mechanical support through the egg-box profile of the outer pipe. Thus, the new concept has the same bedding characteristics as a traditional corrugated plastic drainpipe. The HYDROLUIS concept is based on the assumption that about 70% of the water entering the drainpipes is the result of radial flow from underneath the pipes (Cavelaars et al., 2006). The outer pipe has an egg-box profile to create an open space between the two pipes through which the water can flow upward to the perforations in the inner pipe. The two outside rows of perforations on the top of the inner pipe allow the water to flow into the inner pipe and the row of perforations in the middle ensures that no airlock is created. The space between the two pipes determines the flow velocity and thus the filter functions of the pipe. This space can be adjusted depending on the design discharge; for example, for pipes up to 200 mm diameter the space is 8 mm, corresponding to an open surface area of 160 cm² m⁻¹. The opening size of the perforations in the inner pipe is 2 × 4 mm, corresponding to a surface area varying between 25.3 (for Ø 80 mm pipes) to 56 cm² m⁻¹ (for Ø 200 mm pipes) which is typical for perforated pipes and conforms to international standards (Deutsches Institut für Normung, 1982; Komo, 1976; Nijland et al., 2005). As the open surface area where the water enters between the two pipes is larger than the area of the perforations, the hydraulic function will increase because the entrance resistance will be

![Figure 1. Working principle of the HYDROLUIS pipe-envelope combination.](https://wileyonlinelibrary.com)
reduced. In a ‘traditional’ drain envelope system, water velocity increases when the water flows toward the perforations. This increases the risk of soil particle movement that may result in either clogging of the envelope or sediment entering the pipe. In irrigated agriculture, this is particularly risky after irrigation when the groundwater table rises well above drain level and consequently increases the hydraulic head. In this new concept, the velocity of the water decreases when it flows upward between the two pipes. This significantly reduces the movement of soil particles and thus the risk that these particles enter the inner drainpipe. The lighter and smaller particles that will stay in suspension during this upward movement will stay in suspension when they enter the inner pipe, eliminating or minimizing the risk of clogging and/or sedimentation.

For installation, the unperforated inner pipes and the outer pipes are transported in separate rolls to the field and put in place during installation. A punching device has been developed that is also mounted on the top of the trench box of the drainage machine (where the inner pipe enters the trench box) to perforate the inner pipe during installation. This guarantees that the perforations are in the correct position. A second, specially developed, device installed at the bottom end of the trench box wraps the outer pipe around the inner pipe at the moment the drainpipe is placed in the trench. In this way, the correct geometry of the drainpipe envelope is ensured. In 2016, the new concept was certificated by the Turkish Bureau of Standardization (Türk Standardlari Enstitüsü, 2016).

A second risk and problem for subsurface drains in irrigated agricultural lands is root penetration, because of the favourable humid conditions in the drainpipe (air and water). This often happens when the groundwater table falls below drain level. In the new HYDROLUIS concept, root penetration is eliminated because the space between the inner and outer pipes is either saturated (when the groundwater table is above drain level) or only filled with air (when the groundwater table is below drain level) (Figure 2). Both conditions, i.e. a water-lock by high groundwater levels and an airlock by low groundwater levels, prevent root penetration.

Figure 2. The space between the inner and outer-pipe is either saturated (when the groundwater table is above drain level) or filled with just air (when the groundwater table is below drain level). [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 3. Location of Harran pilot area. [Colour figure can be viewed at wileyonlinelibrary.com]
In this paper, the results of a field test of the new pipe-envelope concept in a pilot area in Harran Province, central Turkey, are presented.

**MATERIALS AND METHODS**

**Pilot area**

The field study was conducted at the GAPTAEM research station (50 ha) near Harran (36° 56' 44" N, 38° 54' 44" E), which is located in south-eastern Turkey 30 km south of city of Şanliurfa at an altitude of about 400 m (Figure 3). The test site is representative of the Şanliurfa Harran Plain, an area of about 150 000 ha that is already under irrigation and where subsurface drainage systems are required. Irrigation water is supplied from the Atatürk Dam via two tunnels (Olcay Unver, 1997).

The climate in the Harran Plain is arid and hot in summer, cold and rainy in winter. The average annual precipitation and evaporation are respectively 365 and 1850 mm and the average temperature is 17°C (Table I). The distribution of precipitation over the seasons is 56% in winter, 30% in spring, 1% in summer and 13% in autumn. The average number of rainy days is 70 and number of days with snow is 3. The crops grown in the area are wheat and barley in winter and cotton, corn and vegetables in summer. Olive trees are also grown in a small part of the area, but are not

| Treatment | Depth (cm) | Sat. cap. (%) | Texture (%) | Class | pH | ECe (dS m⁻¹) | Lime (%) |
|-----------|------------|---------------|-------------|-------|----|--------------|---------|
| Control   | 0–30       | 78            | 24 Sand     | 56 Clay | 20 Silt | Clay | 7.6      | 0.7 | 30   |
|           | 30–60      | 74            | 24 Sand     | 58 Clay | 18 Silt | Clay | 7.7      | 0.9 | 30   |
|           | 60–90      | 70            | 22 Sand     | 58 Clay | 20 Silt | Clay | 7.8      | 1.2 | 30   |
|           | 90–120     | 74            | 22 Sand     | 58 Clay | 20 Silt | Clay | 7.7      | 1.2 | 30   |
|           | 120–150    | 68            | 32 Sand     | 44 Clay | 24 Silt | Clay | 7.8      | 0.9 | 30   |
|           | 150–180    | 74            | 26 Sand     | 48 Clay | 26 Silt | Clay | 7.8      | 0.8 | 30   |
|           | 180–210    | 77            | 24 Sand     | 54 Clay | 22 Silt | Clay | 7.8      | 0.7 | 30   |
| Geotextile| 0–30       | 71            | 24 Sand     | 66 Clay | 20 Silt | Clay | 7.6      | 0.8 | 31   |
|           | 30–60      | 70            | 24 Sand     | 56 Clay | 20 Silt | Clay | 7.7      | 1.1 | 29   |
|           | 60–90      | 71            | 20 Sand     | 58 Clay | 22 Silt | Clay | 7.7      | 1.4 | 30   |
|           | 90–120     | 73            | 20 Sand     | 60 Clay | 20 Silt | Clay | 7.6      | 1.7 | 30   |
|           | 120–150    | 74            | 22 Sand     | 58 Clay | 20 Silt | Clay | 7.6      | 1.6 | 32   |
|           | 150–180    | 83            | 22 Sand     | 56 Clay | 22 Silt | Clay | 7.8      | 1.0 | 32   |
|           | 180–210    | 79            | 22 Sand     | 58 Clay | 20 Silt | Clay | 7.9      | 0.8 | 29   |
| Gravel    | 0–30       | 70            | 22 Sand     | 56 Clay | 22 Silt | Clay | 7.6      | 0.8 | 30   |
|           | 30–60      | 71            | 24 Sand     | 56 Clay | 20 Silt | Clay | 7.7      | 0.9 | 29   |
|           | 60–90      | 69            | 24 Sand     | 56 Clay | 20 Silt | Clay | 7.7      | 1.0 | 29   |
|           | 90–120     | 70            | 22 Sand     | 58 Clay | 20 Silt | Clay | 7.7      | 1.0 | 35   |
|           | 120–150    | 69            | 26 Sand     | 54 Clay | 20 Silt | Clay | 7.6      | 1.1 | 42   |
|           | 150–180    | 74            | 24 Sand     | 56 Clay | 20 Silt | Clay | 7.7      | 0.9 | 43   |
|           | 180–210    | 75            | 20 Sand     | 60 Clay | 20 Silt | Clay | 7.5      | 0.9 | 43   |
| HYDROLUIS | 0–30       | 72            | 22 Sand     | 60 Clay | 18 Silt | Clay | 7.7      | 0.9 | 30   |
|           | 30–60      | 70            | 20 Sand     | 58 Clay | 22 Silt | Clay | 7.6      | 0.9 | 31   |
|           | 60–90      | 70            | 20 Sand     | 60 Clay | 20 Silt | Clay | 7.6      | 0.9 | 32   |
|           | 90–120     | 71            | 22 Sand     | 60 Clay | 18 Silt | Clay | 7.7      | 0.9 | 33   |
|           | 120–150    | 72            | 18 Sand     | 60 Clay | 22 Silt | Clay | 7.6      | 1.0 | 35   |
|           | 150–180    | 73            | 20 Sand     | 62 Clay | 18 Silt | Clay | 7.6      | 1.0 | 33   |
|           | 180–210    | 78            | 22 Sand     | 56 Clay | 22 Silt | Clay | 7.6      | 0.8 | 44   |
included in this research. Wheat and barley are irrigated in the period from March to April and cotton from mid-June to mid-September. Subsurface drainage is required to leach the salts brought in by the irrigation water, as the precipitation in winter is not sufficient to control the soil salinity. If a subsurface drainage system is installed, soil salinity does not occur when the current irrigation practices are followed and additional leaching and amendments are not required (Bahçeci and Nacar, 2009).

The test site has a flat topography and deep alluvial soil profile with A and C horizons (Table II). Soil texture is clayey with a clay content of 50–60%, a lime content of about 30% and a soil pH between 7.1 and 8.0. Soil samples were collected from different soil layers and their respective total porosity and effective porosity were determined in the laboratory by the standard procedures proposed by Braun and Kruijne (2006). Although soils with a clay content >60% generally do not need a filtering envelope, in this region the soils are less stable so envelopes are prescribed in the tenders.

Monitoring programme

In the test plot, plastic drainpipes were installed at an average depth of 1.50 m, a slope of 0.1%, a length of about 200 m and at 60 m spacing. Four drainpipe–envelope combinations were tested:

1) Sand–gravel filter envelope around the drainpipe. It should be noted that these natural sand–gravel envelopes generally do not match the design specifications (Türk Standardlari Enstitüsü, 2016);
2) Pre-wrapped geotextile (PP450) (Turkish Standard TSE K 445 Plastic Fibre Wrapping Material for Pipe);
3) HYDROLUIS pipe–envelope combination;
4) No envelope material (control).

Thus, the new HYDROLUIS pipe–envelope concept was compared with two commonly used envelopes (sand–gravel and PP450) and a control plot with no envelope. For each combination, three field drains were connected to a collector drain through a manhole (Figure 4). Hydraulic heads were measured in three rows of observation wells: midway between the drains, adjacent to the drainpipe just outside the drain trench and inside the drainpipe (Figure 5). The head differences were used to assess the entrance resistances for the four drain/envelope combinations based on the classification proposed by Cavelaars et al. (2006) (Table III). Measurements were repeated three to four times a day to obtain data for different hydraulic heads. Water samples of the

Figure 4. Measurement and observation network: each combination consists of three field drains connected to a collector drain through a manhole.

Figure 5. Principle of drainage testing: (A) Four stages of water flow towards and inside the drains; (B) Head losses in the four stages (Cavelaars et al., 2006).
drain outflow were collected for pH, EC and silt-load analyses. The monitoring programme started in 2015, but only a limited amount of data could be collected, thus the monitoring programme was repeated in 2016. An excavation programme was conducted to check whether the envelopes were clogged and/or sedimentation had taken place in the drainpipes. At the end of each season, root growth was manually checked using a video system. Data were analysed using the SPSS 20.0 statistical package. All the treatment means were compared for significant differences using the Student t-test at significant level of $P < 0.05$.

**RESULTS AND DISCUSSION**

The results of the 2015 monitoring programme are presented in Table IV. The drain performance of the HYDROLUIS pipe–envelope combination and the gravel envelope was good, but the performance of the geotextile was moderate to poor. The entrance resistance in the control plot was not measured, thus the drain performance for the control could not be established. For all four combinations, the sediment load was measured. The control plot had the highest sediment load (0.0046% or 46 g m$^{-3}$). The sediment load in the drains with geotextile and the HYDROLUIS combination were respectively 24% (sediment load of 35 g m$^{-3}$) and 26% (sediment load of 34 g m$^{-3}$) lower than that of the control plot. The gravel envelope had by far the lowest sediment load (26 g m$^{-3}$), 43% lower than the control. There was no significant difference between treatments in term of pH and EC values of the drain discharges, and the siltation values were not high when evaluated in terms of irrigation water.

The results of the monitoring programme for the four combinations tested in 2016 are presented in Table V. In the plot equipped with the HYDROLUIS pipe–envelope system, the average drain discharge was 0.062 l s$^{-1}$ or 2 mm day$^{-1}$. This value is lower than the design drainage coefficient of 3.6 mm day$^{-1}$ used in the ongoing projects in the Harran Plain (Bahçeci and Nacar, 2009). The average hydraulic head midway between the drains was 14.9 cm; the head just outside the drain trench ($h_{\text{trench}}$) was 2.4 cm and the head just outside the pipe 1.4 cm (Figure 6). The average entrance resistance was 0.07, with a standard deviation of 0.03 (Table V). The entrance resistance of the HYDROLUIS pipe–envelope system was significantly lower than that of the geotextile, sand–gravel and control at the $P < 0.05$ level. Based on the criteria presented in Table III, the entrance resistance can be classified as ‘normal’ and the drain performance as ‘good’.

The entrance resistance of the gravel envelope, with an average of 0.38 and a standard deviation of 0.04 (Table V), can be classified as ‘high’ and the drain performance as ‘moderate’. The entrance resistance of the geotextile was

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**Table III. Performance criteria to evaluate entrance resistance and drain performance of pipe drains (Cavelaars et al., 2006)**

| $h_y(h_2 + h_3)$ | Entrance resistance | Drain performance |
|-----------------|---------------------|------------------|
| $<0.3$          | Normal              | Good             |
| $0.3–0.6$       | High                | Moderate to poor |
| $>0.6$          | Excessive           | Very poor        |

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**Table IV. Drain performance values for different drain–envelope combinations (2015)**

| Envelope–pipe combination | $h_y(h_2 + h_3)$ (–) | Drain performance | $pH$ | EC (dS m$^{-1}$) | Sediment load (%) |
|----------------------------|-----------------------|-------------------|------|-----------------|-------------------|
| Gravel                     | 0.25                  | Good              | 7.2  | 0.96            | 0.0026            |
| Geotextile                 | 0.38                  | Moderate to poor  | 7.5  | 0.99            | 0.0035            |
| HYDROLUIS                  | 0.28                  | Good              | 7.0  | 0.97            | 0.0034            |
| Control                    | –                     | –                 | 7.2  | 1.03            | 0.0046            |

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**Table V. Average groundwater levels, hydraulic heads and entrance resistances for the four combinations tested in 2016**

|                                | No. of observations | $H$ (cm) | $h_2$ (cm) | $h_3$ (cm) | $h_{\text{pipe}}$ | $h_{\text{trench}}$ | Entrance resistance$^*$ |
|--------------------------------|---------------------|----------|------------|------------|-------------------|---------------------|--------------------------|
| HYDROLUIS pipe–envelope system | 18                  | 14.9     | 12.5       | 1.0        | 1.4               | 2.4                 | 0.07 (0.03) $^a$ $^+$    |
| Sand–gravel envelope           | 4                   | 13.8     | 8.4        | 5.3        | 0.1               | 5.4                 | 0.38 (0.04) $^b$         |
| Geotextile                     | 10                  | 11.0     | 4.5        | 7.2        | −0.7              | 6.5                 | 0.61 (0.14) $^a$         |
| Control: without envelope      | 6                   | 10.5     | 16.8       | 11.4       | −17.7             | −6.3                | 0.50 (0.27) $^b$ $^c$     |

$^*$Between brackets: standard deviation.

$^+$Values in the same column that do not have letters in common are significantly different at the $P < 0.05$ level.
0.61 with a standard deviation of 0.14 (Table V). This is significantly higher than the gravel and the HYDROLUIS pipe-envelope system and can be classified as ‘excessive’; subsequently the drain performance is ‘very poor’. The performance of the geotextile envelopes in 2016 was significantly poorer compared to 2015, suggesting a clogging problem in the envelope. The excavation programme that was conducted confirmed this finding (see next section, ‘Visual inspection and excavation programme’). Finally, in the control plot, the average entrance resistance was 0.49 with a standard deviation of 0.27 (Table V) and can thus be classified as ‘high’ and the drain performance was ‘moderate to poor’. There is, however, no significant difference between the

Table VI. Classification of the entrance resistance and drain performance for the four drain–envelope combinations

| Pipe–envelope combination | 2015 | 2016 |
|---------------------------|------|------|
|                           | $h_3/(h_2+h_3)$ | Entrance resistance | Drain performance | $h_3/(h_2+h_3)$ | Entrance resistance | Drain performance |
| Gravel                    | 0.25 | Normal | Good | 0.38 | Normal | Moderate |
| Geotextile                | 0.38 | Normal | Moderate | 0.61 | High | Very poor |
| HYDROLUIS                 | 0.28 | Normal | Good | 0.07 | Normal | Good |
| Control                   | –   | –       | –     | 0.49 | High | Moderate to poor |

Table VII. Sediment load and salinity (EC) of the drainage effluent for the four drain–envelope combinations in 2016

| Date       | HYDROLUIS |          | Geotextile |          | Gravel |          | Control |          |
|------------|-----------|----------|------------|----------|--------|----------|---------|----------|
|            | Solid matter (%) | EC (dS m$^{-1}$) | Solid matter (%) | EC (dS m$^{-1}$) | Solid matter (%) | EC (dS m$^{-1}$) | Solid matter (%) | EC (dS m$^{-1}$) |
| 3.05.2016  | 0.071     | 0.78     | 0.074     | 1.01     | 0.100  | 1.03     | 0.118   | 1.09     |
| 4.05.2016  | 0.068     | 0.78     | 0.067     | 1.00     | 0.095  | 1.20     | 0.108   | 1.26     |
| 5.05.2016  | 0.066     | 0.78     | 0.079     | 0.95     | 0.093  | 1.21     | 0.126   | 1.05     |
| 9.05.2016  | 0.060     | 0.79     | 0.070     | 1.03     | 0.084  | 1.12     | 0.112   | 1.34     |
| Average    | 0.066     | 0.79     | 0.072     | 1.00     | 0.093  | 1.14     | 0.116   | 1.19     |

Figure 6. Average hydraulic head in the HYDROLUIS pipe-envelope system.

Figure 7. Visual inspection for sedimentation in the four drain-envelope combinations: from left to right: gravel – geotextile - HYDROLUIS combination - control. (Note: the vertical orientation of the photos is misleading because of the moving camera). [Colour figure can be viewed at wileyonlinelibrary.com]
performance of the control and both the geotextile and sand-gravel envelopes.

When we compare the four drain-envelope combinations for both years, we can conclude that the HYDROLUIS drain-envelope combination had a normal entrance resistance and good drain performance (Table VI). The gravel envelope scored second with a normal entrance resistance and moderate to good drain performance. Both performed much better than the geotextile and the drain without an envelope in the control plot.

The sediment load and the salinity of the drainage effluent for the four combinations were measured four times in 2016 (Table VII). In the plots with the HYDROLUIS pipe-envelope system, the sediment load was lowest, and it can be concluded that there was no clogging or sedimentation in the pipelines.

**Visual inspection and excavation programme**

On 14 June 2016, a visual inspection of the four drain-envelope combinations was conducted using a video camera with the aim of finding out if there was any sedimentation or root growth in the drainpipes. The drainpipes were also excavated for a visual inspection of root growth and sedimentation inside the pipe. Sedimentation was found in the gravel, geotextile and control pipes, but it is clearly visible that the HYDROLUIS combination did not have any sedimentation in the pipe (Figure 7). The excavation shows that

| Production costsa |  |
|------------------|------------------|
| (TL m⁻¹)         | (€ m⁻¹)b        |
| PVC pipe (Ø 100 mm) | 2.47 | 0.55 |
| HYDROLUIS pipe–envelope combination | 6.50 – 7.50 | 1.45–1.68 |
| Pre-wrapped pipe and PP 450 envelope | 7.00 – 9.50 | 1.57–2.21 |
| Pipe and graded gravel filter | 13.00 – 18.00 | 2.91–4.02 |

*Transportation costs not included.

*Exchange rate €1.00 = TL 4.47 (6 November 2017).
the pipe with the geotextile envelope was completed clogged and filled with sediment (Figure 8).

Root growth was limited in all combinations, probably because all the fields were cultivated with annual crops (wheat, barley, corn and cotton), but it can be seen that the HYDROLUIS combination did not have any roots inside the pipe (Figure 9). These first results indicate that with the use of the HYDROLUIS combination, root growth of annual crops was negligible. Further research, however, is needed to monitor root growth in the subsurface drains in the area where perennial crops, e.g. olive trees, are grown.

Costs of pipes and envelopes

The costs of the HYDROLUIS pipe–envelope combination and pre-wrapped envelopes are comparable, but significantly lower than for a gravel envelope (Table VIII). The gravel envelopes are even more expensive due to high transport costs, but these costs are not taken into consideration as transport costs vary from project to project depending on the hauling distance. The installation speed of a trenched installing the HYDROLUIS pipe–envelope combination is comparable to that of the installation of a geotextile envelope: for example, in the Trakya region on a rather soft soil the installation speed of a trenched with the HYDROLUIS system was approximately 11 m min\(^{-1}\) or 1200 m day\(^{-1}\) (personal communication Contractor, 1/08/2017).

Quality control

Quality control for the HYDROLUIS pipe–envelope combination is quite straightforward. The quality control of the production of the inner and outer pipes is similar to that for perforated corrugated plastic pipes and is well documented in national and international norms and standards (Nijland et al., 2005). As previously mentioned, the two pipes are put in place during installation using specially developed extensions that are positioned on the trench box. The installation is a three-step process (Figure 10):

1) The unperforated inner drainpipe is guided into the trench box (Figure 10a);
2) A punching device perforates the inner pipe when it enters the trench box; this ensures that the perforations are indeed at the correct location on the top of the drainpipe (Figure 10b);
3) At the bottom end of the trench box a second attachment folds the outer pipe around the inner pipe (Figure 10c).

In this way the correct geometry of the pipe–envelope combination is ensured, as twisting of the pipe in the trench hardly ever happens (Figure 10d). Thus additional quality checking of the envelope is not required, a considerable saving compared to the cost of quality control for the (graded) gravel. The installation of gravel envelopes is also much more cumbersome and error-prone because it requires almost perfect logistical management during installation to ensure its effectiveness (Ritzema et al., 2006).

CONCLUSION

HYDROLUIS, a new drain–envelope concept, has been developed to overcome the problems of clogging, sedimentation and root growth inside subsurface drainpipes. The new concept consists of a corrugated inner pipe with three rows of perforations on the top and an unperforated outer pipe that covers about 2/3 of the inner pipe leaving only the bottom, unperforated part of the inner pipe in contact with the soil. In a pilot area in Harran, Turkey, the new concept was tested and compared to traditionally used gravel and synthetic (PP450) envelopes and a control with no envelope. Based on a 2-year monitoring programme, it can be concluded that the HYDROLUIS pipe–envelope combination performed significantly better than the other three combinations. The HYDROLUIS combination had a ‘normal’ entrance resistance and ‘good’ drain performance. The gravel envelope scored second also with a ‘normal’ entrance resistance,
but with only ‘moderate’ to ‘good’ drain performance. Both performed much better than the drains with a geotextile envelope or no envelope, although the differences between the control, gravel and geotextile were not significant. The performance of the geotextile envelopes was significantly poorer in 2016 compared to 2015, due to clogging.

Other advantages of the HYDROLUIS pipe–envelope combination are that no signs of sedimentation or plant root penetration into the pipes were observed for the annual crops grown in the pilot area. The geometry of the HYDROLUIS pipe–envelope combination prevents or reduces deformation of the pipes by providing mechanical support through the egg-box profile of the outer pipe. The production and transportation costs are comparable to the cost of a pre-wrapped synthetic envelope and considerably lower than for a gravel envelope. Two specially developed devices that are positioned on the trench box guarantee quality of construction. It can be concluded that the HYDROLUIS envelope can be a good alternative for sand/gravel or synthetic envelopes on irrigated lands. Although the new concept looks promising, more field research is recommended to verify long-term resistance to root growth, especially for perennial crops, and performance under other soil, hydrological and agricultural conditions.

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