Journal of Hydrology 556 (2018) 339–348

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Estimating drain flow from measured water table depth in layered soils under free and controlled drainage

Samaneh Saadat [a,*], Laura Bowling [b], Jane Frankenberger [a], Eileen Kladivko [b]

[a] Dept. of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907, United States
[b] Dept. of Agronomy, Purdue University, West Lafayette, IN 47907, United States

ARTICLE INFO

Article history:
Received 14 June 2017
Received in revised form 30 August 2017
Accepted 1 November 2017

This manuscript was handled by P. Kitanidis, Editor-in-Chief, with the assistance of Nunzio Romano, Associate Editor

Keywords:
Drain flow estimation
Drainage water management
Layered soil
Hydraulic conductivity profile
Hooghoudt
Filling gap

ABSTRACT

Long records of continuous drain flow are important for quantifying annual and seasonal changes in the subsurface drainage flow from drained agricultural land. Missing data due to equipment malfunction and other challenges have limited conclusions that can be made about annual flow and thus nutrient loads from field studies, including assessments of the effect of controlled drainage. Water table depth data may be available during gaps in flow data, providing a basis for filling missing drain flow data; therefore, the overall goal of this study was to examine the potential to estimate drain flow using water table observations. The objectives were to evaluate how the shape of the relationship between drain flow and water table height above drain varies depending on the soil hydraulic conductivity profile, to quantify how well the Hooghoudt equation represented the water table–drain flow relationship in five years of measured data at the Davis Purdue Agricultural Center (DPAC), and to determine the impact of controlled drainage on drain flow using the filled dataset. The shape of the drain flow–water table height relationship was found to depend on the selected hydraulic conductivity profile. Estimated drain flow using the Hooghoudt equation with measured water table height for both free draining and controlled periods compared well to observed flow with Nash-Sutcliffe Efficiency values above 0.7 and 0.8 for calibration and validation periods, respectively. Using this method, together with linear regression for the remaining gaps, a long-term drain flow record for a controlled drainage experiment at the DPAC was used to evaluate the impacts of controlled drainage on drain flow. In the controlled drainage sites, annual flow was 14–49% lower than free drainage.

1. Introduction

Long records of continuous drain flow are important for quantifying annual and seasonal changes in the subsurface drainage flow from drained agricultural land. This is essential for quantifying load, used for determining the contribution of tile drains to nutrient loads and the impact of practices that have the potential to reduce loads. Yet monitoring drain flow is challenging; equipment malfunction caused by power interruption, lightning strikes, and animals, often causes data corruptions or interruptions.

One practice that requires long-term flow records to properly evaluate is controlled drainage (CD), a practice used to reduce the transport of nitrate through tile drainage to surface waters by using a water control structure to vary the depth of the drainage outlet. Nitrate loss from tile drains with CD systems has been shown to be between 17% and over 80% lower than conventional drainage (Skaggs et al., 2012a). But monitoring challenges have made quantification difficult. Gunn et al. (2015) stated that instrument failure and outlet submergence reduced measured drain flow records in a field in Ohio and limited understanding of the effects of controlled drainage at the field scale. Adeuya et al. (2012) discussed the restriction in drain flow measurements from two drained farms in Indiana because of the submergence conditions of the outlet that required empirical data correction before load calculation. Cooke and Verma (2012) found that uncertainties associated with the flow measurements due to the errors in the low flow measurements and the submergence conditions were the main reasons for uncertainty in annual flow and load estimations. When drain flow data has gaps, other measurements such as water table depth at a monitoring site may provide additional data that can be used in estimating the missing drain flow.

The relationship between midpoint water table height above drain (m) and drain flow (q) has been investigated in the

* Corresponding author.
E-mail addresses: ssaadat@purdue.edu (S. Saadat), bowling@purdue.edu (L. Bowling), frankenb@purdue.edu (J. Frankenberger), kladivko@purdue.edu (E. Kladivko).

https://doi.org/10.1016/j.jhydrol.2017.11.001
0022-1694/

laboratory or with field experiments since the 1950s (Luthin and Worstell, 1957; Goins and Taylor, 1959; Hoffman and Schwab, 1964). Luthin and Worstell (1957) analyzed field data collected by other researchers and showed that the relationship between m and q was approximately linear for homogeneous soils. Goins and Taylor (1959) also found a linear relationship between m and q under field conditions when the water table is falling continuously. However, Hoffman and Schwab (1964) found that for an anisotropic soil the m–q relationship was not linear, in contrast to the results for homogeneous soils.

Several theoretical equations have been developed for subsurface drainage design since 1940 that use the relationship between m and q (Hooghoudt, 1940; Kirkham, 1958; Van Schilfgaarde, 1963; Yousfi et al., 2014). The Hooghoudt equation assumes an elliptical water table profile below the soil surface, in which q varies with the squared m. Van Schilfgaarde (1963) proposed a theoretical tile-spacing equation for a falling water table in homogeneous soils. Hooghoudt developed the equivalent depth term, and then a correction in the van Schilfgaarde equation was made by substituting the equivalent depth for the thickness of the water-bearing zone (Bouwer and van Schilfgaarde, 1963). Although in these equations the goal was to facilitate drainage design, these equations have been used to estimate q from m in DRAINMOD (Skaggs, 1978) and also to determine the effective hydraulic conductivity (K_e) of wetland soils (Skaggs et al., 2008).

According to Goins and Taylor (1959), tile flow is more related to the position of the water table in the soil profile than to the height of the water table above the drain (m), because of the strong influence of the hydraulic conductivity profile in drainage. The saturated hydraulic conductivity (K) is a time-invariant physical parameter that varies with depth in the soil column under most field conditions. The K_e depends on the water table position in the soil profile and therefore varies over time as the water table depth changes. The Hooghoudt equation assumes a K that is constant with depth, which can be unrealistic under most field conditions.

Hydrologic models have assumed various hydraulic conductivity profiles. TOPMODEL assumes that K declines exponentially with depth (Beven and Kirkby, 1979), while Ambroise et al. (1996) generalized the TOPMODEL concepts by incorporating different K (transmissivity) profiles within the original TOPMODEL. They introduced two alternative forms of subsurface K profiles including linear and parabolic, and showed how the different K profiles can lead to different streamflow recession curves. In the DRAINMOD model, a layered soil profile is assumed with each layer having a different K (Skaggs et al., 2012b). Depending on the water table position, a K_e is calculated as a weighted average of the saturated layers. The impact of the various representations of K in layered soils to the relationship between m and q has not been fully recognized, even though the strong influence of conductivity in the soil profile on the drain flow was stated half a century ago (Goins and Taylor, 1959).

Drain flow and water table depth data have been collected at the Davis Purdue Agricultural Center (DPAC) to evaluate the hydrological and environmental effects of CD. However, the drain flow record is not complete due to monitoring challenges, preventing the calculation of annual flow and limiting the conclusions about nutrient loads. The flow measurement limitation provides a motivation to develop a new method for estimating drain flow using measured water table depths.

The objectives of this paper are therefore to (1) explore the m–q relationship using different K profiles in the Hooghoudt equation, (2) evaluate how well drain flow estimated based on the Hooghoudt equation represented the measured flow at this field site, and (3) determine the effect of CD on drain flow by estimating drain flow using water table depth observations with the Hooghoudt equation for the entire monitoring period.

2. Materials and methods

2.1. Experimental site and field measurements

The Davis Purdue Agricultural Center (DPAC) is a research farm in eastern Indiana located at 40.266°N, 85.160°W (Fig. 1). The controlled drainage experimental site is the 0.16 km^2 (39-acre) field (field W), split into four quadrants, northwest (NW), southwest (SW), northeast (NE), and southeast (SE) with areas of 3.5 ha, 3.5 ha, 3.6 ha, and 3.7 ha. The elevation change in this field is approximately 3 m (<1% slope). Soils at the site consist of Blount (silty clay loam, somewhat poorly drained), Condit (silty loam, poorly drained), Pewamo (clay loam, very poorly drained) and Glynwood (silt loam, moderately well drained) series, based on an Order 1 soil survey completed in 2001 (Blumhoff et al., 2001). The drainage system was installed in September 2004 with laterals having an approximate depth of 1 m and spacing of 14 m (Utt, 2010). Each of the quadrants has its own 15 cm (6 inch) sub-main that connects to the outlet and empties into the 20 cm (8 inch) main outlet at the northwest corner of the field. Drainage in the SE and NW quadrants was controlled during some periods while the SW and NE were allowed to drain conventionally at all times. A more detailed description of this site can be found in Saadat et al. (2017).

The subsurface drain flow was monitored with two different methods throughout the study period. The original method of monitoring drain flow used pressure transducers to measure water level in a circular flume installed in the subsurface drain (Brooks, 2013), but the flow obtained from this method is uncertain because of frequent submergence of the outlet and errors associated with the measurements. Therefore, these measurements were not used in this study. Since 2012, flow has been measured every hour by electromagnetic flow meters (Krohne Waterflux 3070) that are installed downstream of the control structures (Fig. 1) and offer

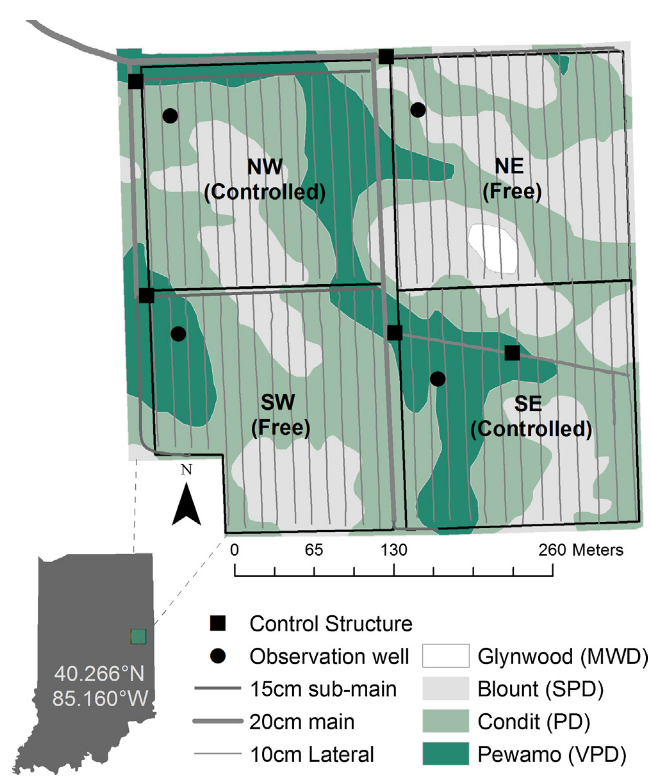

Fig. 1. Map of Field W at Davis Purdue Agricultural Center with soil type, tile drain location and observation well and control structure location (MWD: moderately well drained; SPD: somewhat poorly drained; VPD: very poorly drained).