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

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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

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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

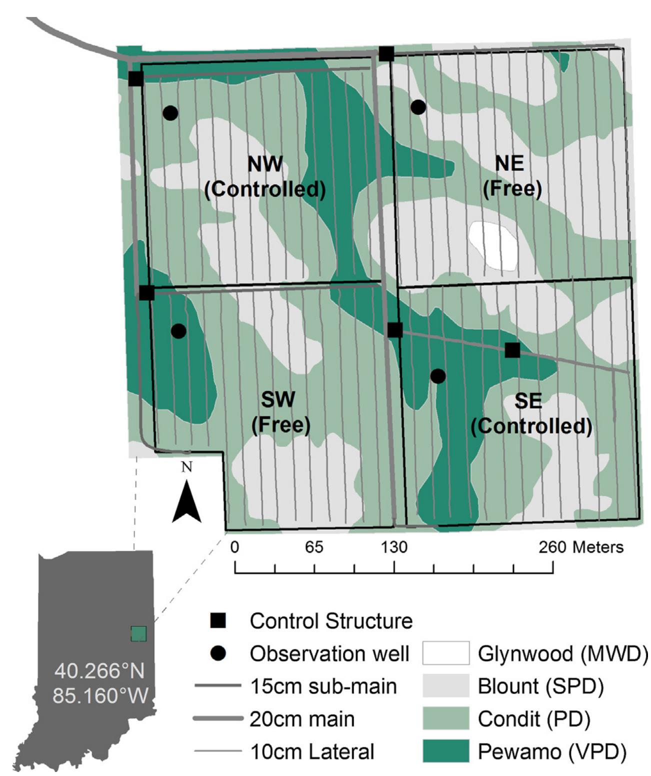

Fig. 1. Map of Field W at Davis Purdue Agricultural Center with soil type, tile drain location and observation well and control structure location (MWD: moderately well drained; SPD: somewhat poorly drained; VPD: very poorly drained).

the advantage of accurately measuring both forward and backward flow at very low flow as well as high flow levels (Brooks, 2013). Drain flow is often restricted downstream of the field by the subsurface county main with limited capacity, and therefore backward flow can occur at times of high flow, particularly in the lowest (NW) quadrant. Having a measure of backward flow enables the calculation of the net drain flow that exits the field. Electromagnetic flow meters require a signal converter to power the flow meter and provide a user interface to view or change the settings. The signal converters, however, have stopped working many times due to major lightning strikes and for this reason and other sensor malfunctions, drain flow data is often missing in each of the quadrants (Table 1).

Water table depth was measured throughout the entire 11-year period using observation wells in each quadrant, located at the midpoint between two drains and within the expected area of influence of CD based on an elevation difference relative to the outlet of less than 0.3 m (Bou Lahdou, 2014) (Fig. 1). These wells were perforated 5-cm PVC pipe installed to a depth of approximately 2 m. Pressure transducers (Global Water WL-16) measured water table level every hour, and data were stored in a data logger fitted inside the top of the pipe. In one of the quadrants (SW), maintenance that required removing and replacing the water table elevation sensor in the observation well led to uncertainty in the absolute water table elevation. The sensor measures water table relative to the sensor depth, so during periods between maintenance activities the recorded water table elevation was adjusted up or down by a fixed amount relative to the drain elevation, based on the assumption that drains flow only when water table is above the drain. Details of this process are provided in Saadat et al. (2017). Water table depth measurements from June 2006 to December 2016 were used in this study.

2.2. Hooghoudt equation

The Hooghoudt equation (Bouwer and van Schilfgaarde, 1963) was used to estimate drain flow based on the measured water table depth. This steady state equation is one of the best known of the theoretical drainage equations, and is widely used for design and research purposes as selected for use in the DRAINMOD model (Skaggs, 1978). Using experimental field data, Ferro (2016) found that the Hooghoudt, Kirkham (1958) and Yousfi et al. (2014) theoretical equations for drainage design under steady-state conditions had similar performance in estimating the ratio of height of water above drain (m) over drain spacing (L), therefore, any of these equations can be used for practical applications. In reality, drainage is a non-steady state process but a good approximation of drain flow can be obtained from the steady state formula presented by Hooghoudt.

$$q = \frac{4K_e m(2d_e + m)}{L^2} \qquad (1)$$

where q is the drain flow (cm hr^{-1}), m is the midpoint water table height above the drain (cm) for free drainage and above the drain outlet weir (cm) for controlled drainage, K_e is the effective lateral hydraulic conductivity of the profile (cm hr^{-1}), L is the distance between drains (cm) and d_e is the equivalent depth from the drain to the impermeable layer (cm) and can be obtained from the following equations presented by Moody (1966).

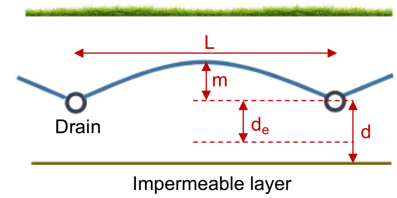

Fig. 2. Schematic of the Hooghoudt drain flow formula parameters.

$$d_e = \frac{d}{1 + \frac{d}{L}\left[\frac{8}{\pi}\ln\left(\frac{d}{r}\right) - \alpha\right]} \qquad 0 < d/L < 0.3 \qquad (2)$$

$$d_e = \frac{L\pi}{8\left[\ln\left(\frac{L}{r}\right) - 1.15\right]} \qquad d/L > 0.3 \qquad (3)$$

where d is the depth of the impermeable layer below drains (cm), and r is the effective drain radius. Alpha can be found by:

$$\alpha = 3.55 - \frac{1.6d}{L} + 2\left(\frac{2}{L}\right)^2 \qquad (4)$$

The equivalent depth (d_e) was substituted for d in equation 1 in order to correct the resistance due to radial flow, when assuming flow towards the drains is only horizontal. The equivalent depth represents an imaginary thinner soil layer below the drains, shown in Fig. 2, through which the same amount of water will flow per unit time as in the actual situation with combined radial and horizontal flow (Ritzema, 1994).

2.3. Hydraulic conductivity profiles

The saturated lateral hydraulic conductivity (K) varies with depth in many soils, and three different theoretical profiles representing the variation in K with depth were compared to explore how the shape of the relationship between q and m varies depending on K profile. The first was a constant profile, based on the assumption of homogeneous soil in the original form of the Hooghoudt equation meaning that the K is constant with depth. The second is a layered profile, calculating an equivalent effective hydraulic conductivity (K_e) for parallel flow through a layered soil profile based on equation 4, similar to what is used in DRAINMOD (Skaggs, 1978):

$$K_e = \frac{\sum_{i=1}^{n} K_i d_i}{\sum_{i=1}^{n} d_i} \qquad (5)$$

where K_i is the hydraulic conductivity and d_i is the saturated thickness of soil layer i, as shown in Fig. 3 and n is the number of layers in the soil profile. K_e is determined in each time step before every flow calculation and it depends on the position of water table because the thickness of the saturated zone in each layer (d_i) varies linearly with the water table position within the layer. If the water table is below the layer, d_i is zero, while if the water table is above the layer, d_i is equal to the layer thickness, D_i.

Table 1
Number of missing days in drain flow observations obtained from the electromagnetic flow meters.

Quadrant	2012	2013	2014	2015	2016
NE	119	177	149	172	110
NW	24	18	149	2	59
SE	119	263	178	73	163
SW	24	18	95	180	14

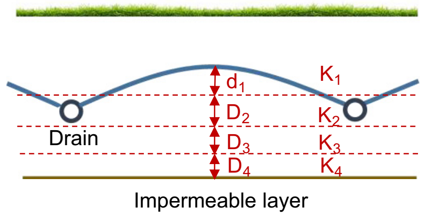

Fig. 3. Schematic of layered soil with each having a different hydraulic conductivity.

The third profile was an exponential decline in K with depth, which is used for example in TOPMODEL (Beven and Kirkby, 1979) and other models (e.g. DHSVM, Wigmosta et al., 1994). The saturated hydraulic conductivity (K) at each depth is given by (Louis, 1974):

$$K(d) = K_0 e^{\alpha(d)} \tag{6}$$

where K_0 is the hydraulic connectivity at the ground surface, α is the decay exponent defining the exponential relationship between K and depth and d is the depth below the ground surface (Fig. 4).

Hydraulic conductivity (K) is commonly calibrated in models, since it tends to be higher than K values measured in the laboratory or in the field (Chappell et al., 1998; Blain and Milly, 1991). Hoffman and Schwab (1964) also stated that K computed from tile outflow is believed to be a better estimate for tile design than that determined from core and auger-hole measurements.

In the current paper, the Hooghoudt equation was calibrated with respect to observed m and q by adjusting the K and depth of each layer for the constant and layered K profiles. In each time step, the effective lateral hydraulic conductivity of the profile (K_e), which is dependent on the water table position, was calculated using the conductivity and depth values for each layer, before the flow estimation. K values and layer depths were allowed to change in the range reported in the official Soil Survey for these soil series. For each K value and depth, drain flow calculated using the Hooghoudt equation was compared with observations and this process continued until the best efficiency and lowest bias between observed and estimated drain flow were obtained. Because many different combinations of K values provided a high efficiency with low bias, the visual fit between the m–q relationship from the observed data and the Hooghoudt equation was another criteria. K values that resulted in an even distribution of observations around the Hooghoudt equation were retained. A Matlab script was written to automate calibration of the Hooghoudt equation by adjusting K values in the range of 0.1–0.8 m/day, and layer depths in the defined range for representative soil series at each quadrant (Soil Survey Staff, 2017). The Pewamo soil series was used to represent the two southern quadrants because it is a very poorly drained soil and will tend to have a higher drain flow compared to other soil series at these plots; in addition, observation wells are located at this soil series. For the two northern quadrants, the Condit was selected, because it was at the well location and compared to the Blount, it is a more poorly drained soil.

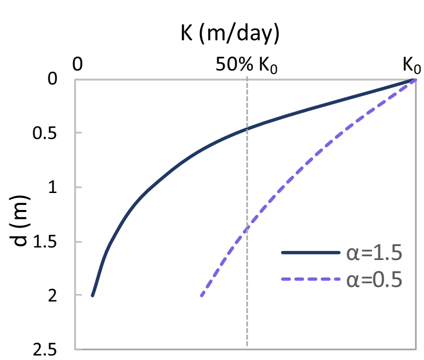

Fig. 4. The exponential relationship between saturated hydraulic conductivity and depth with two different decay exponents.

Instead of calibrating the Hooghoudt equation for the exponential K profile, the equivalent exponential profile was obtained based on the calibrated K values. The hydraulic conductivity at the ground surface (K_0 in Eq. (5)) was assumed to be equal to the calibrated hydraulic conductivity of the first layer in the layered profile (K_1). The decay exponent (α in Eq. (5)) was then adjusted to yield an equivalent profile to the layered K profile.

2.4. Drain flow evaluation

Drain flow was estimated for each hour for which water table depth was available, using the calibrated Hooghoudt equation and measured water table depths. Drain flow estimates were calibrated and validated by comparing them with field observations both visually and statistically. Daily flow estimates and measurements from 2012 to 2015 were used for calibration, and then estimated and measured drain flow from 2016 were used for validation. The goodness of fit statistics were used for evaluating the drain flow estimation results including the Nash-Sutcliffe efficiency coefficient (NSE), the percent bias or error (PE) and correlation coefficient (R^2):

$$NSE = 1 - \frac{\sum_1^n (O_i - P_i)^2}{\sum_1^n \left(O_i - \overline{O_i}\right)^2} \tag{7}$$

$$PE = \frac{\sum_1^n P_i - \sum_1^n O_i}{\sum_1^n O_i} \times 100 \tag{8}$$

$$R^2 = \sqrt{\frac{\sum_1^n (O_i P_i - n\bar{O}\bar{P})^2}{\left(\sum_1^n O_i^2 - n\left(\bar{O}\right)^2\right)\left(\sum_1^n P_i^2 - n\left(\bar{P}\right)^2\right)}} \tag{9}$$

where O_i is the daily measured value, P_i is the daily simulated,$\overline{O_i}$ is the average of measured values,$\overline{P_i}$ is the average of simulated values, and n is the number of observed values. The NSE assesses the predictive power of a hydrological model and the R^2 is a measure of how well trends in the estimated values follow trends in the observed values. The NSE value can vary between minus infinity and 1, with 1 indicating a perfect fit. The value of R^2 can vary from zero to 1, with 1 indicating a perfect linear relationship between the observed and simulated values. The PE value can vary from minus infinity to positive infinity. A negative value indicates under-prediction, and positive value indicates over-prediction.

2.5. Filling missing values with regression approach

After gaps in drain flow data were filled using the Hooghoudt equation and water table depth observations, gaps in drain flow estimates remained due to missing values in the water table observations (Table 2). These missing values were estimated in order to accurately calculate monthly and annual values of drain flow. The regression approach has been widely used for filling data gaps (Tomer et al., 2003; Haddad et al., 2010) and was selected for this study. Linear regression equations of the daily flow observations from one quadrant against a paired quadrant with the same

Table 2
Number of remaining missing days after drain flow estimates combined with observations.

Quadrant	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
NE	20	39	43	4	36	21	0	22	0	0	61
NW	0	88	2	0	148	32	1	2	0	0	1
SE	60	210	52	37	25	38	28	76	0	23	20
SW	0	51	0	7	24	14	0	15	0	23	0

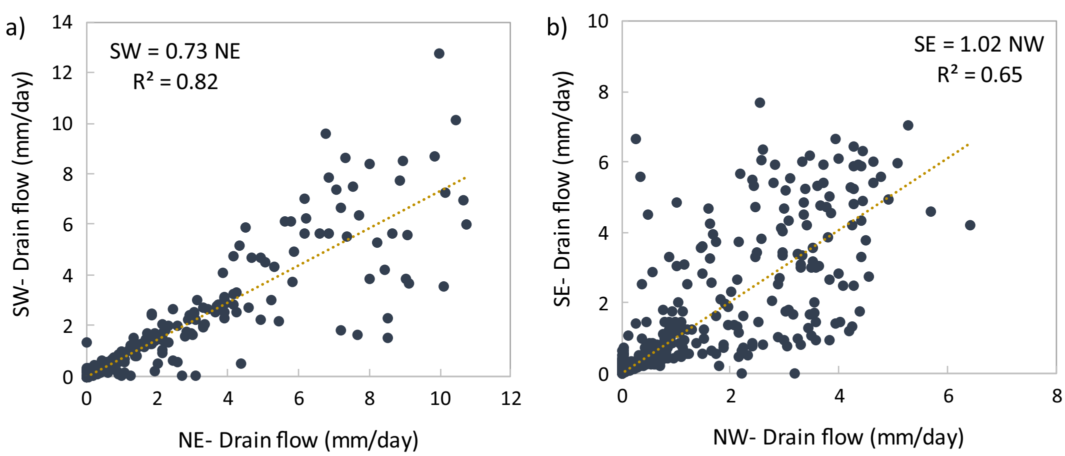

Fig. 5. Linear regression equations of daily drain flow observations from 2012 to 2016 for a) free quadrants and b) controlled quadrants.

treatment (free or controlled drainage) were developed and utilized to fill the missing values (Fig. 5).

3. Results and discussion

3.1. Implication of different K profiles on the m–q relationship

The constant, exponential, and layered K profiles are shown in Fig. 6 for the SW quadrant. For the layered profile, calibrated K values by layer for each quadrant (Table 3) were used. The total depth of the soil profile is defined by d_e. The K is higher in the top layer in the NW and SW quadrants, but higher in the bottom layer in the NE and SE quadrants. The soil series at the well location for both SE and SW are the same, however, the proportions and locations of different soils within these quadrants are different and that can affect on the calibrated K values. The reason for having a larger conductivity in the bottom layer of two quadrants is unknown; one possible reason may be a sand layer below the tile drain or other heterogeneity in this glacial landscape. For the constant profile, K was also calibrated while for the exponential profile, an equivalent profile to the layered soil (Table 4) was used to maintain the same average conductivity.

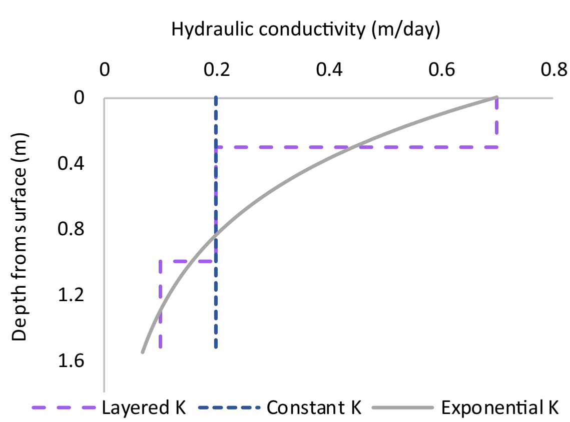

Fig. 6. Soil profile for the SW quadrant with three different K profiles (layered K, constant K and exponential K).

Fig. 7 shows how the Hooghoudt equation can represent the m–q relationship differently from a linear to parabolic relationship depending on the selected conductivity profile. Different K profiles resulted in a different relationship between m and q except for the NW quadrant where both constant and layered K profiles revealed almost the same relationship. In all cases, the constant K profile yields an approximately linear relationship that is consistent with earlier observations (Luthin and Worstell, 1957; Goins and Taylor, 1959). These results indicate that there is not any conflict between the previous observations and the Hooghoudt equation, since Hooghoudt can appear linear if the constant K profile is used in the equation. However, the relationship between m and q is not always linear for all fields and the correct K profile should be recognized and used in the Hooghoudt equation.

Table 3
Calibrated soil layers and saturated lateral hydraulic conductivity for each individual layer.

NW		SW		NE		SE	
Soil layer (cm)	K (m/day)	Soil layer (cm)	K (m/day)	Soil layer (cm)	K (m/day)	Soil layer (cm)	K (m/day)
0–25	0.6	0–30	0.7	0–25	0.25	0–30	0.25
25–160	0.15	30–100	0.2	25–140	0.2	30–100	0.2
160–178	0.1	100–155	0.1	140–164	0.6	100–146	0.6

Table 4
The constant and exponential K profiles used in Figs. 6 and 7.

Quadrant	K (m/day)	
	Constant*	Exponential**
NE	0.3	0.25 e $^{(0.6\ d)}$
SW	0.2	0.7 e $^{(-1.5\ d)}$
NW	0.15	0.6 e $^{(-d)}$
SE	0.5	0.25 e $^{(0.7\ d)}$

* Calibrated.
** Equivalent with calibrated K values for each soil layer.

These relationships are consistent with expected behavior. In homogeneous soils, K is constant with depth, and therefore, when water table drops through the soil profile, drain flow decreases proportionally which results in an approximately linear plot of the m versus q. However, in the layered soils, K_e depends on the water table position in the soil profile. This could lead to a non-linear relationship between m and q in the layered soils. For example, if the top soil layer has a higher K (e.g. SW and NW quadrants), when the water table is near the surface, the higher K is the predominant factor in the K_e as reported by Hoffman (1963). Therefore, when water table is in this layer, drain flow decreases proportionally to a drop in water table. However, when the water table drops below the top layer, the K of other layers are predominant and usually lower than the top layer and this can lead to a decrease in flow while water table has not decreased correspondingly.

3.2. Drain flow estimates using layered K profile

Among the three discussed hydraulic conductivity (K) profiles, the layered K profile was chosen for prediction of drain flow because the layered K profile is more physically representative, due to its relation to soil horizons in the soil profile. This allows consideration of an anomalous layer such as a sand layer in between other soil layers while the non-monotonic changes in K with depth is not accurately representable by the exponential profile. The layered K profile is also more physically realistic due to soil compaction impacts on conductivity. In homogenous soils that K is assumed constant, soil compaction can decrease the K exponentially with depth, while K, which is related to the soil texture, can vary for different soil layers in the layered K profile.

The relationship between observed daily m versus observed q and the observed m versus estimated q from the Hooghoudt equation using layered K profile (Table 3) in the calibration period are shown in Fig. 8. In this figure, rising water table events are separated from falling water table events to examine potential hysteresis in the m versus q relationship for the entire drainage period. However, the difference was found to be small for daily values and since the main goal of this analysis was to estimate drain flow for the entire drainage period, both falling and rising events were considered together in the analysis. Drain flow is also constrained by the hydraulics of the drainage pipes. For the outlet drains of these 3.5 ha quadrants, which consist of corrugated pipes with diameter 15 cm at a slope of 0.1%, the maximum flow is estimated to be 10 mm/day (ASABE Standards, 2015). In the NW quadrant, the hydraulic limit is lower because of an undersized outlet for the field, and was set at 6 mm/day based on observed maximum flow. The SE quadrant also appeared to have a lower flow limit, but the 10 mm value was used since there was no known physical basis for a lower limit and other factors such as errors in the water table depth and drain flow measurements might have contributed to those scattered high water table events in this quadrant.

Daily estimated and observed drain flow for the four-year calibration period were in good agreement (Table 5). Drain flow was under-predicted in the NE and SE quadrants and over-predicted in the SW and NW quadrants, with the lowest PE of 2% and the

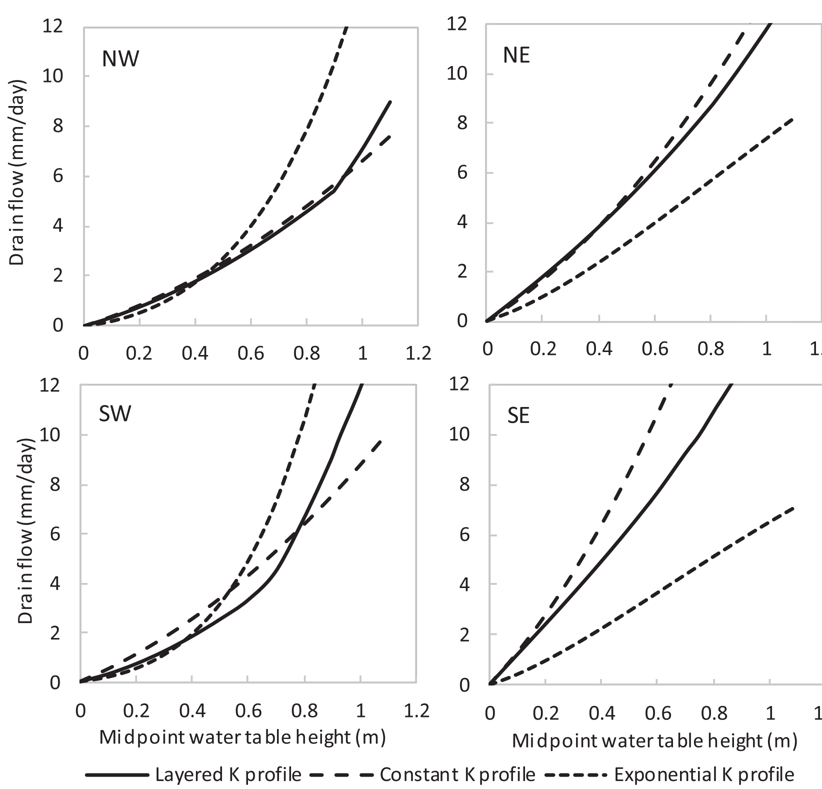

Fig. 7. The relationship between observed drain flow and midpoint water table height above drain (for free drainage) or above the outlet weir (for controlled drainage) with the application of different K profiles in the Hooghoudt equation.

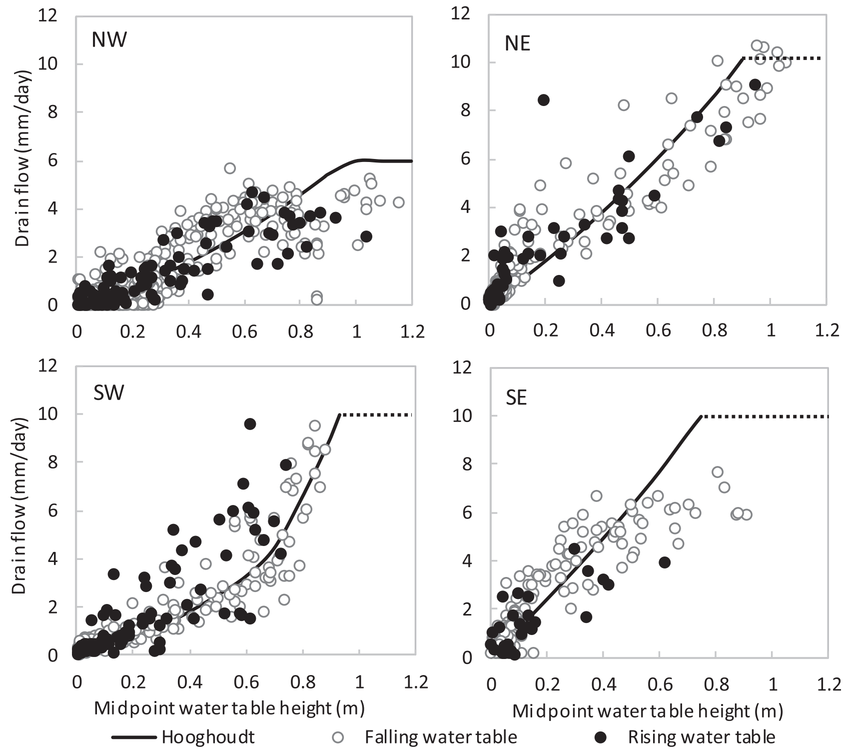

Fig. 8. The relationship between observed drain flow and midpoint water table height above drain (for free drainage) or above the outlet weir (for controlled drainage) and the Hooghoudt equation using layered K profile with the dashed line showing the constraint on the flow.

highest of −15% in the SW and SE quadrants, respectively. In general, free draining and controlled quadrants performed similarly in predicting drain flow. Although the NW, which is a controlled quadrant, had lower NSE, other factors such as restriction of drain flow through the main may be contributing to the lower performance of this quadrant in predicting flow. In order to better understand the effect of controlled drainage on flow prediction, free drainage and controlled drainage periods were separated and results showed that even in free drainage periods, the NW had lower efficiency than other quadrants (NSE = 0.7).

Time series of predicted and observed drain flow were plotted and compared visually. An example for 9 months in the SW quadrant is shown in Fig. 9. Besides the high values obtained for the NSE, visual inspection of this figure also indicates a good agreement between estimated and observed drain flow.

Validation of the method using calibrated K_e was conducted by comparing estimated and observed drain flow for 2016 (Fig. 10). Values obtained for both R^2 and NSE were above 0.8 for all four quadrants, indicating a good agreement between estimated and observed values. NSE values of 0.91 and 0.84 for estimated drain flow in SW and NW quadrants, respectively, were even higher than that in the calibration period and for the other two quadrants NSE were in a similar range.

Table 5
Statistical measures of agreement between daily estimated and measured drain flow in the calibration period (percent error (PE) regression coefficient (R^2) and Nash-Sutcliffe Efficiency (NSE)).

Quadrant	PE (%)	R^2	NSE
NE (Free)	−10	0.90	0.87
SW (Free)	2	0.82	0.84
NW (Controlled)	11	0.76	0.72
SE (Controlled)	−15	0.87	0.85

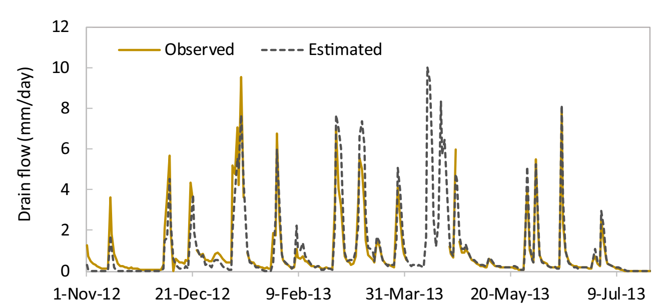

Fig. 9. Comparison of daily observed and estimated drain flow for the SW quadrant during seven months of study.

Predicted and observed drain flow were also compared on a monthly basis to determine whether the relationship predicts drain flow more accurately in some months than others (Fig. 11). This figure indicates the differences between the total monthly values of predicted and observed drain flow including months when both observed and predicted values were available for all days. In some months, there was a complete drain flow dataset at least in one of the years, however, there was not any year with observation data for October in the NE and for December in the SE quadrants. In general, months with higher flow had more disagreement between observed and predicted values specifically in the NW quadrant. Once again, due to the downstream flow restrictions in the outlet, backward flow occurred in this quadrant resulting in observed values that are lower than predictions. The highest difference was in the NW quadrant in June 2015 with around 36 mm over-prediction, which occurred during very high flow. Total precipitation was 265 mm/month, while the 10-year mean precipitation for this month is only 135 mm/month. Backward flow occurred in this quadrant more than 5% of the time during this month, and the over-prediction indicates an error in the method when

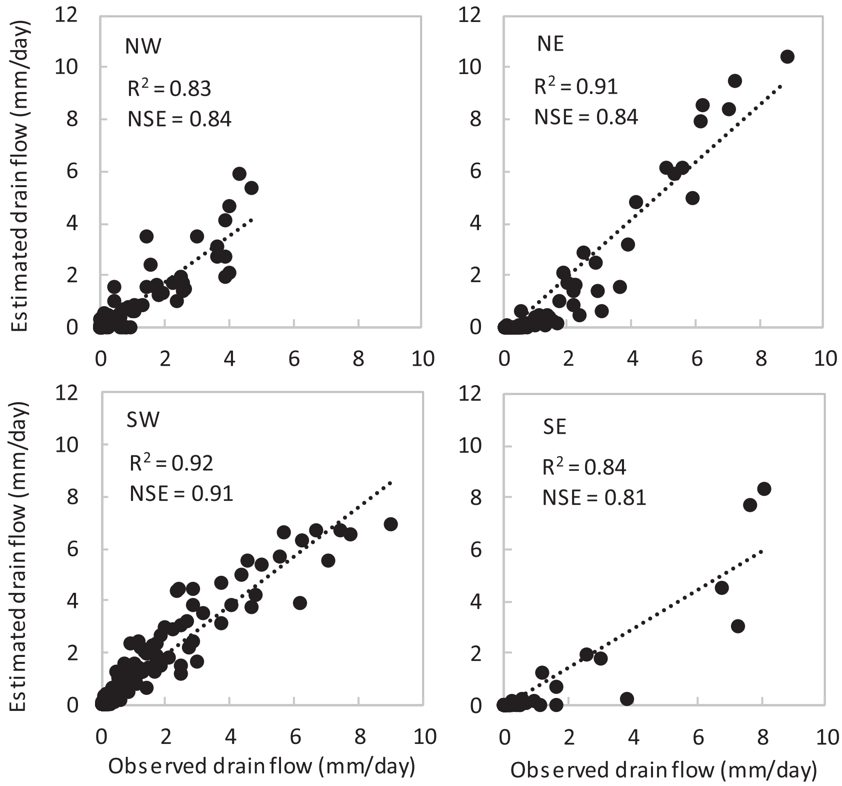

Fig. 10. Estimated daily drain flow versus observed drain flow and regression coefficient (R2) and Nash-Sutcliffe Efficiency (NSE) values for each quadrant for the validation year (2016).

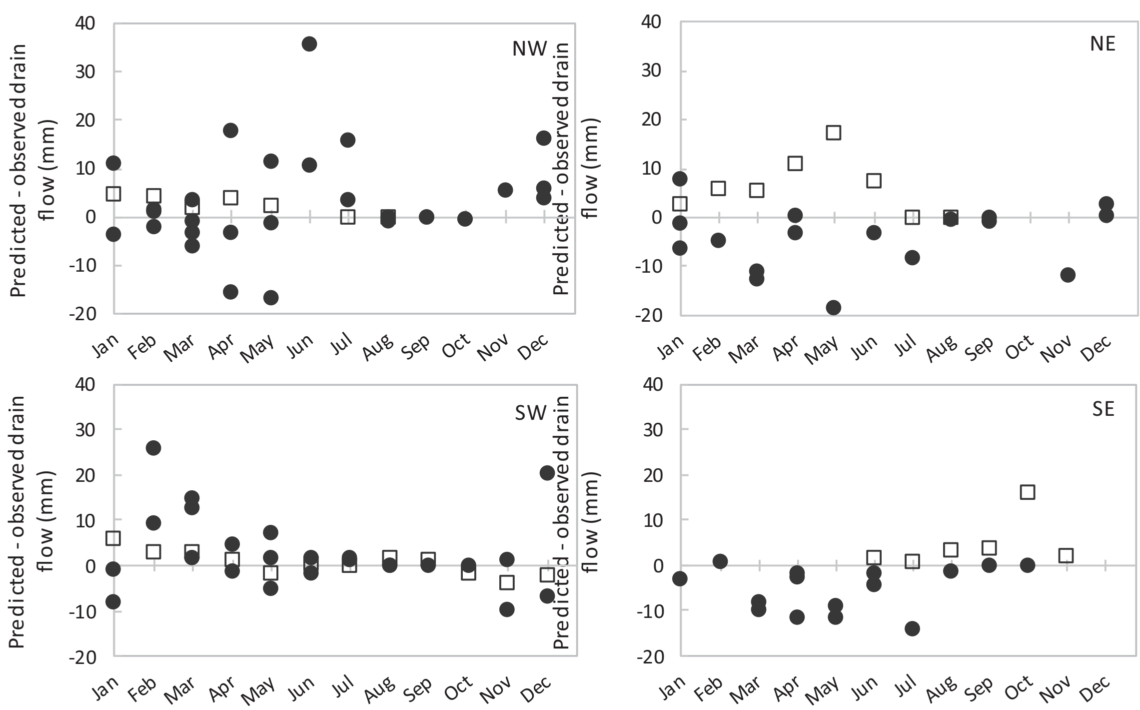

Fig. 11. Comparison of observed and predicted monthly drain volume (mm) for months with complete drain flow datasets for both calibration and validation periods (Each dot represents a different year in the calibration period and square represents the validation period).

flow is restricted downstream. This could be addressed in future work by considering separately the periods when the pipes are pressurized by looking at the pressure transducer data (available only for some periods at this site).

Overall, results indicate that calibrated K_e and the Hooghoudt equation did a good job in predicting daily drain flow from water table depth observations and this method can be used to estimate drain flow for the entire period of study. However, there are uncertainties associated with this method. The Hooghoudt equation is not a perfect representation of the physical system, and the high variability of K over the field limits precision. Measurement uncertainties related to the water table and drain flow values can lead to parameter uncertainty in calibration of the Hooghoudt equation. The flow meter had an accuracy better than ±2% at all flow levels and ±0.2% at higher flow (Krohne Waterflux 3070, 2016) and the uncertainty related to the water level sensors was ±0.2% of the full range (Global Water WL-16 Water, 2016). An additional source of uncertainty for this experimental field could be more due to the limitation caused by the drain outlet and backward flow that sometimes occurred and the fact that this method is not able to take the backward flow into account.

3.3. Effect of controlled drainage on drain flow

Hourly drain flow was estimated for the whole range of water table heights from July 2006 through December 2016 using the calibrated K_e and the Hooghoudt equation. Estimated drain flow was combined with observations for the periods that drain flow were accurately measured at DPAC (2012–2016) while only estimates of drain flow were used for the former years of study (2006–2011). The remaining gaps in drain flow were then filled using linear regression equations and the filled flow record used to determine the effect of controlled drainage at this site by comparing annual and monthly drain flow in free and controlled quadrants.

Time series for 11 years of annual drain flow and precipitation are shown in Fig. 12. Annual drain flow tended to follow the same trend for all quadrants except for the SE quadrant in 2008 when annual flow decreased while it increased in other quadrants. This could be due to the large number of missing days in this quadrant in the previous year (2007: 210 missing days) that has led to a higher flow value where the paired quadrant regression has been used for filling the gaps. Between the two free quadrants, the NE usually has higher flow compared to the SW quadrant, possibly because of a neighboring farm that allowed water to enter towards the northeast section of the experimental field. Overall, annual drain flow followed the annual trends in precipitation; as total precipitation increased, annual flow increased.

Annual drain flow for both free quadrants was greater than controlled quadrants. The overall reduction in drain flow with CD over the 11-year period was 1182 mm. The 11-year averages of annual drain flow and flow rate for each quadrant are given in Table 6. The average annual drain flow of the two free and the two controlled quadrants was also calculated and compared for each year. The results showed that the average annual drain flow of controlled quadrants was lower than free quadrants in all years between 14% and 49%. This reduction is comparable to other findings reported in the literature, as Adeuya et al. (2012) found a 15–24% decrease in annual drain flow with CD from a field in Indiana. Similarly, reductions of 18% to over 85% in the average annual flow

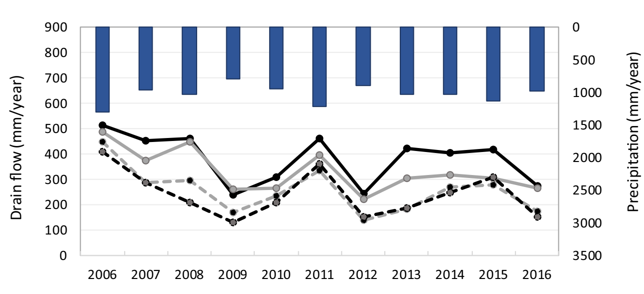

Fig. 12. Time series of annual drain flow and total precipitation from 2006 to 2016.

Table 6
Mean (2006–2016) flow rate and annual drain flow for 11 years.

Quadrant	Average flow rate (mm/day)	Average annual flow (mm/year)
NE	1.07 ± 0.27*	381 ± 97
SW	0.92 ± 0.23	331 ± 84
NW	0.69 ± 0.29	256 ± 89
SE	0.73 ± 0.49	241 ± 90

* Mean ± standard deviation.

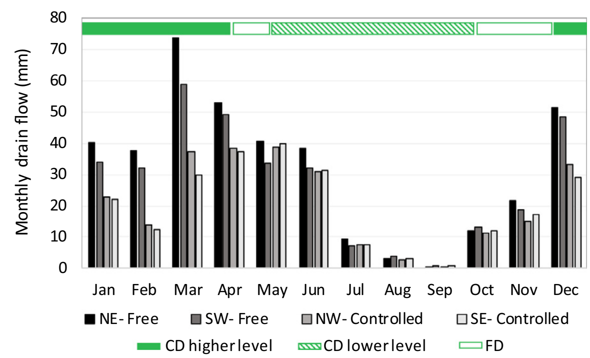

Fig. 13. The average of complete observations of monthly drain flow for 10 years of study (from 2006 to 2016). CD higher level is when the outlet is raised to 0.9 m and the lower level is when the outlet is raised to 0.6 m above the drain.

with CD have been reported in the review by Skaggs et al. (2012a), which included results from Illinois, Iowa, North Carolina and Ohio and also Sweden and Ontario. More recently, Williams et al. (2015) also reported 8–34% reduction in the annual flow with CD from a site in Ohio.

The 11-year average of monthly drain flow (Fig. 13) indicates the seasonal changes in drain flow. As expected, during the months that drainage was controlled, monthly drain flow was greater in free quadrants than controlled. In other months such as May, June, July, October and November the average flow in controlled quadrants was more similar to the free quadrants. In these months, the height to which the outlet was raised in the control structure was lower than other months of control, or no management was done at that time and all quadrants were freely drained. This relatively higher flow in controlled quadrants during the months that all quadrants were freely drained or the outlet was not raised as high as other months, again, indicates the effectiveness of the controlled drainage in reducing monthly flow.

4. Conclusions

This study explores how variation in hydraulic conductivity (K) with depth within field sites affects the observed relationship between midpoint water table height above drain and drain flow. This clarifies interpretation of field results and demonstrates that the Hooghoudt equation may still be applicable, even when field data does not show the classic parabolic curve. With this understanding, this study demonstrates that drain flow can be estimated from the Hooghoudt equation using water table depth measurements.

Examination of the shape of the relatoinship of the water table height above drain (m) and drain flow (q) under various K profiles showed that the Hooghoudt equation can be linear or parabolic depending on the selected K profile. Drain flow estimated from water table height using the layered K profile and the Hooghoudt equation compared well to observed flow in both calibration and validation periods, suggesting that this method could be used to fill in or extend the incomplete drain flow records when water table depth measurements are available. Using this method, together with linear regression for the remaining gaps, a long-term drain flow record for a controlled drainage (CD) experiment at the Davis Purdue Agriculture Center was used to evaluate the impacts of CD on drain flow. In the controlled drainage quadrants, annual flow was 14–49% lower than free drainage. The annual flow reductions ranged from 67 mm/year to 200 mm/year over the 11-year study period. In the future, these filled data sets will be used to evaluate the effect of CD on the nutrient losses through subsurface flow. The long record of continuous drain flow will help to better evaluate the effects of CD on water quality and allow for a better understanding of the annual and seasonal changes in both the hydrological and environmental impacts of CD.

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