Uniwersytet Przyrodniczy w Poznaniu
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Wpływ sterowania odpływem drenarskim na wybrane elementy gospodarki wodnej gleb i straty azotu na obszarze zdrenowanym

Impact of controlling outflow on selected elements of soil water management and nitrogen losses at drainage facility

Rozprawa doktorska w dziedzinie nauk inżynieryjno-technicznych
w dyscyplinie inżynieria środowiska, górnictwo i energetyka
Doctoral thesis in engineering and technology sciences
in the environmental engineering, mining and energy discipline

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Wykaz artykułów naukowych

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P1. Kęsicka, B., Stasik, R., Kozłowski, M. (2022). Effects of modelling studies on controlled drainage in agricultural land on reduction of outflow and nitrate losses–a meta-analysis. *PLOS ONE*, *17*(4), e0267736: 1-21. DOI: 10.1371/journal.pone.0267736.

IF (2022): 3.700 wg Journal Citation Reports (JCR), **100 pkt** wg listy Ministerstwa Edukacji i Nauki (MEiN)

P2. Kęsicka, B., Kozłowski, M., Stasik, R. (2023). Effectiveness of Controlled Tile Drainage in Reducing Outflow and Nitrogen at the Scale of the Drainage System. *Water,* 15, 1814: 1-20. DOI: 10.3390/w15101814.

IF (2023): 3.400 wg JCR, **100 pkt** wg MEiN

P3. Kęsicka, B., Kozłowski, M., Stasik, R., Pińskwar, I. (2023). Controlled Drainage Effectiveness in Reducing Nutrient Outflow in Light of Climate Changes. *Applied Sciences*, 13, 9077. DOI: 10.3390/app13169077.

IF (2023): 2.700 wg JCR, **100 pkt** wg MEiN

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SPIS TREŚCI

Wykaz stosowanych skrótów

CD – *ang. controlled drainage* – drenowanie kontrolowane

DWM – *ang. drainage water management* – zarządzanie gospodarką drenarską

EU – *ang. European Union* – Unia Europejska

FD – *ang. free drainage* – konwencjonalny drenowanie

GWT – *ang. groundwater table* – poziom wody gruntowej

GFDL – *ang. Geophysical Fluid Dynamics Laboratory* – Model Laboratorium Geofizycznej Dynamiki Płynów

IMGW-PIB – *ang. Institute of Meteorology and Water Management – National Research Institute* – Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy

ISIMIP3b – *ang. Inter-Sectoral Impact Model Intercomparison Project* – Projekt Porównawczy Międzysektorowego Modelu Oddziaływania z uwzględnieniem protokołu 3b określającego wpływ zmian klimatycznych na warunki społeczno-ekonomiczne

JCWP – *ang. Surface Water Body* – Jednolita część wód powierzchniowych

MPI – *ang. Max Planck Institute Earth Model* – Model Systemu Ziemi Instytutu Maxa Plancka

N – *ang. nitrogen* – azot

$N\text{-}NO_3$ – *ang. nitrate-nitrogen* – azot azotanowy (V)

P – *ang. phosphorus* – fosfor

RETC – *ang. RETention Curve* – program wykorzystywany do określania właściwości hydraulicznych gleb nienasyconych

SSP370 – *ang. Shared Socioeconomic Pathway* – scenariusz klimatyczny dla wspólnej ścieżki społeczno-gospodarczej SSP3 „Rywalizacja regionalna” dla wariantu wymuszenia radiacyjnego osiągniętego do roku 2100 wynoszącego 7 W/m^2 w jednostkach dziesiątych watów.

UKESM – *ang. UK Earth System Model* – Brytyjski Model Systemu Ziemi

Streszczenie

Rolnictwo jest jednym z sektorów szczególnie wrażliwych na dostępność wody. Na skutek zachodzących zmian klimatu i związanych z tym zmian rozkładu czasowego i przestrzennego opadów atmosferycznych poszukuje się nowych rozwiązań adaptacyjnych do zmieniających się warunków. Pomocne mogą okazać się systemy drenarskie powiązane z obszarami rolniczymi jako jednofunkcyjne sieci odwadniające. Możliwa jest zmiana dotychczasowej funkcji poprzez zastosowanie prostego rozwiązania pozwalającego na wstrzymanie odpływów drenarskich, czyli praktyki kontrolowanego odpływu.

Celem niniejszej rozprawy doktorskiej było określenie wpływu stosowania kontrolowanego odpływu drenarskiego na wybrane elementy gospodarki wodnej gleb i jakość odpływów wód drenarskich uchodzących do pobliskich wód powierzchniowych. Badania terenowe wykonywano na obiekcie drenarskim Ostrowo Szlacheckie w dziale drenarskim 42 w latach 2019-2020. Po dwa poddziały drenarskie przeznaczono na dwie różne praktyki drenowania, w tym na drenowanie konwencjonalne, nazywane też w literaturze swobodnym (FD – free drainage) i drenowanie kontrolowane (CD – controlled drainage). Na podstawie pomiarów i badań terenowych, analiz fizyczno-chemicznych gleb i odpływów drenarskich oraz prac kameralnych określono dane wejściowe do modelowania. Rejestrowane poziomy zwierciadła wód gruntowych wykorzystano do kalibracji i walidacji modelu DRAINMOD. Ustalono kilka wariantów działania CD dla modelowania przy uwzględnieniu kilku zmiennych warunków meteorologicznych, początkowej głębokości wód gruntowych i terminie rozpoczęcia CD.

Uzyskane wyniki modelowania wykazały, że termin rozpoczęcia praktyki CD ma istotny wpływ na jej efektywność. Na podstawie wykonanych badań można stwierdzić, że najbardziej odpowiedni jest termin 1 marca. Pozwala on na znaczące wydłużenie okresu utrzymywania się zwierciadła wody gruntowej powyżej poziomu ułożenia sączków, również prognozuje się wzrost średniej liczby dni w najbliższej przyszłości. Rozpoczęcie CD w tym terminie pozwala na znaczącą redukcję odpływów drenarskich przez to wpływa na zmniejszenie ilości wynoszonych ładunków biogenów.

Słowa kluczowe: rolnictwo; zmiany klimatu; zarządzanie wodą drenarską; systemy drenarskie; DRAINMOD

Abstract

Agriculture is one of the sectors sensitive to the availability of water. As a result of ongoing climate change and the related changes in the temporal and spatial distribution of precipitation, new adaptation solutions to new conditions are being sought. Drainage systems associated with agricultural areas can be helpful as single-function drainage networks. It is possible to change the current function by using a simple solution that allows stopping drainage outflows, the practice of controlled drainage.

The aim of this doctoral dissertation was to determine the impact of the use of controlled drainage outflow on selected elements of soil water management and the quality of drainage water outflows flowing into nearby surface waters. Field research was carried out at the Ostrowo Szlacheckie drainage facility in drainage section 42 in 2019-2020. Two drainage subdivisions were allocated to two different drainage practices, including conventional drainage, also called free drainage (FD) in the literature, and controlled drainage (CD). Based on measurements and field tests, physical and chemical analyzes of soils and drainage runoff, and chamber work, input data for modeling were determined. The recorded groundwater levels were used to calibrate and validate the DRAINMOD model. Several variants of CD operation were established for modeling, taking into account several variable meteorological conditions, the initial depth of groundwater, and the CD start date.

The obtained modeling results showed that the date of starting CD practice has a significant impact on its effectiveness. Based on the research performed, it was shown that March 1 is the appropriate date. It allows for a significant extension of the period during which the groundwater table remains above the level of drain placement, and an increase in the average number of days is also anticipated in the near future. Starting CD at this date allows for a significant reduction in drainage outflows and reducing the amount of nutrient loads carried away.

Keywords: agriculture; climate change; drainage water management; subsurface drainage; DRAINMOD

1. Wprowadzenie

Pogłębiające się zmiany klimatyczne mają istotny wpływ na przebieg wegetacji roślin uprawnych i stanowią ważne wyzwanie dla produkcji rolnej (Graczyk i Kundzewicz, 2016; Seidenfaden i in., 2022). Wzrost gwałtowności zmian pogody, głównie ulewnych deszczów i okresów długotrwałej suszy wpływają na jakość i wielkość plonów oraz przebieg prac polowych (Bindi i Olesen, 2010; Pińskwar i in., 2020). Ponadto stanowią wyzwanie i przyczyniają się do poszukiwania nowych rozwiązań adaptacyjnych dla rolnictwa. Dla polskiego rolnictwa wyzwaniem jest gromadzenie i zarządzanie wodą bez jej odprowadzenia z obszaru gruntów rolniczych (Michalak, 2020; Prandecki i in., 2021).

Systemy melioracji odwadniających stanowią powszechny element zlewni rolniczej. Systemy drenarskie spełniają głównie funkcję szybkiego i jednostronnego działania, polegającego na odprowadzeniu wód gruntowych obiektu drenarskiego do rowów melioracyjnych. Ponadto tworzą korytarze hydrochemiczne ułatwiające przemieszczanie się wody wraz z rozpuszczonymi związkami biogennymi ze zlewni rolniczej do pobliskich wód powierzchniowych. Wynoszone składniki mineralne stanowią istotny komponent wpływający na rozwój eutrofizacji wód w zlewni Morza Bałtyckiego. W Polsce w latach 70. ubiegłego wieku intensywnie wprowadzano melioracje odwadniające jako najczęściej stosowane rozwiązanie regulacji zależności powietrzno-wodnych użytków rolniczych o okresowym lub trwałym nadmiernym uwilgotnieniu (Ritzema i in., 2006; Bykowski, 2014; Mioduszewski, 2014; Wojciechowska i in., 2018; Refsgaard i in., 2019; Wilk i in., 2019; de Wit i in., 2022).

W ciągu ostatnich lat wzrasta zainteresowanie nowymi rozwiązaniami, pozwalającymi na ograniczenie odpływów podpowierzchniowych i ładunków substancji rozpuszczonych, z uwzględnieniem systemów drenarskich. Jedną z najczęściej stosowanych praktyk jest drenowanie kontrolowane (CD), pozwalające na zastosowanie prostego mechanizmu blokowania lub przebudowy wylotów istniejących systemów w studzienkach drenarskich. Takie rozwiązanie pozwala na kontrolowanie opóźnienia odpływów i zmniejszenie ilości związków azotu i fosforu w wodach odciekających z systemów drenarskich. Ta praktyka jest szeroko stosowana na świecie, najczęściej w Stanach Zjednoczonych (Skaggs i in., 2012) i Kanadzie (Sunohara i in., 2016). Ponadto w krajach europejskich, jak Holandia (Ritzema i Stuyt, 2015), Dania (Rozemeijer i in., 2016; Carstensen i in., 2019; Deichmann i in., 2019), Szwecja (Wesström i Messing, 2007; Wesström i in., 2014), Finlandia (Österholm i in., 2015), Włochy (Tolomio i Borin, 2018; 2019), Litwa (Povilaitis i in., 2018) czy inne kraje, jak Egipt (Wahba i in., 2001).

Dotychczas wykonano wiele eksperymentalnych badań terenowych w celu określenia skutków stosowania CD. Jednak wobec analizy efektów wykorzystania tej praktyki pojawiają się liczne wyzwania. Problematyczne mogą być sytuacje, gdy kampanie pomiarowe nie pozwalają na uzyskanie wystarczającej ilości danych, bądź gdy dąży się do odizolowania innych czynników wpływających na ocenę efektywności CD, takich jak warunki meteorologiczne, czy hydrologiczne. Najczęściej stosuje się wówczas modele symulacyjne, pozwalające na przetestowanie różnych scenariuszy zmian zachodzących pod wpływem CD w gospodarce wodnej rozpatrywanego terenu, na tych samych danych wejściowych i wykluczeniu innych czynników pobocznych wpływających na wyniki. Odpowiednia weryfikacja modelu, poprzez kalibrację i walidację do danych terenowych, pozwala na uniknięcie niepewności uzyskanych wyników. Łączenie danych terenowych z analizami modelowymi pozwala na stworzenie przydatnego narzędzia analitycznego do modelowania różnych zakładanych scenariuszy zmian w gospodarce wodnej gleb na podstawie obecnych lub przyszłych warunków klimatycznych (Häggblom i in., 2019; Sojka i in., 2020; Salla i in., 2022).

Uzasadnieniem podjęcia badań własnych w tym zakresie był brak dotychczas badań z zakresu określenia wpływu CD na ilościowe i jakościowe aspekty gospodarki wodnej terenów zdrenowanych w Wielkopolsce. Właściwa gospodarka wodna obiektów drenarskich ma kluczowe znaczenie dla zmniejszania migracji biogenów do ekosystemów wodnych. Stanowi to aktualny problem podejmowany przez naukowców i decydentów w ramach kształtowania wspólnych kierunków polityki rolnej z uwzględnieniem planów strategicznych odpowiedzialnego gospodarowania wodą dla wszystkich państw członkowskich EU.

2. Cel, zakres pracy i hipotezy badawcze

Celem naukowym pracy była analiza wpływu zastosowania kontrolowanego odpływu drenarskiego (CD) na wybrane elementy gospodarki wodnej gleb oraz ograniczenie strat związków biogennych z obiektu drenarskiego.

Celem praktycznym pracy było wskazanie, które elementy kontrolowanego odpływu, mają istotny wpływ na jej efektywność i mogą w przyszłości stanowić wskazówki dla potencjalnych użytkowników takich systemów drenarskich.

Zakres pracy obejmował:

- określenie efektywności stosowania CD na podstawie danych zawartych w publikacjach naukowych z wykorzystaniem metaanalizy (P1),
- pomiary warunków meteorologicznych, poziomu zalegania wód gruntowych, odpływów drenarskich w ujęciu ilościowym i jakościowym oraz sparametryzowanie środowiska glebowego na wybranym obiekcie drenarskim,
- kalibrację i walidację modelu DRAINMOD na podstawie wyników badań terenowych i analiz laboratoryjnych oraz prac kameralnych pozwalających na określenie charakterystyki sieci drenarskiej, jako niezbędnych danych wejściowych,
- ocenę wpływu zastosowania CD w oparciu o modelowanie, na wybrane elementy gospodarki wodnej i ograniczenie odpływu azotanów, w latach przeciętnych, mokrych i suchych pod względem sum opadów atmosferycznych dla wybranych sezonów wegetacyjnych z lat 1961-2020 na podstawie danych IMGW-PIB (P2),
- ocenę efektywności zastosowania CD w oparciu o modelowanie, na wybrane elementy gospodarki wodnej i ograniczenie strat związków biogennych, dla scenariusza klimatycznego SSP370 najbliższej przyszłości (2021-2050) z uwzględnieniem modeli klimatycznych GFDL, MPI i UKESM (P3).

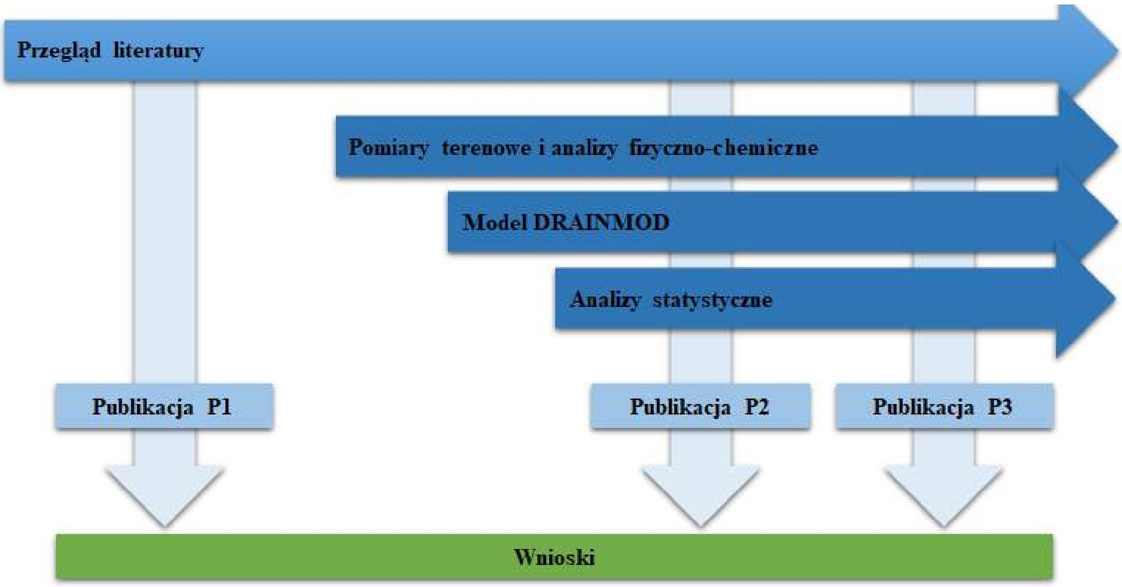
W pracy przyjęto następujące hipotezy badawcze:

H1: Sterowanie odpływem drenarskim istotnie wpływa na poprawę wybranych elementów gospodarki wodnej gleb zdrenowanych.

H2: Sterowanie odpływem drenarskim istotnie ogranicza straty azotu z gleb zdrenowanych.

3. Materiały i metody

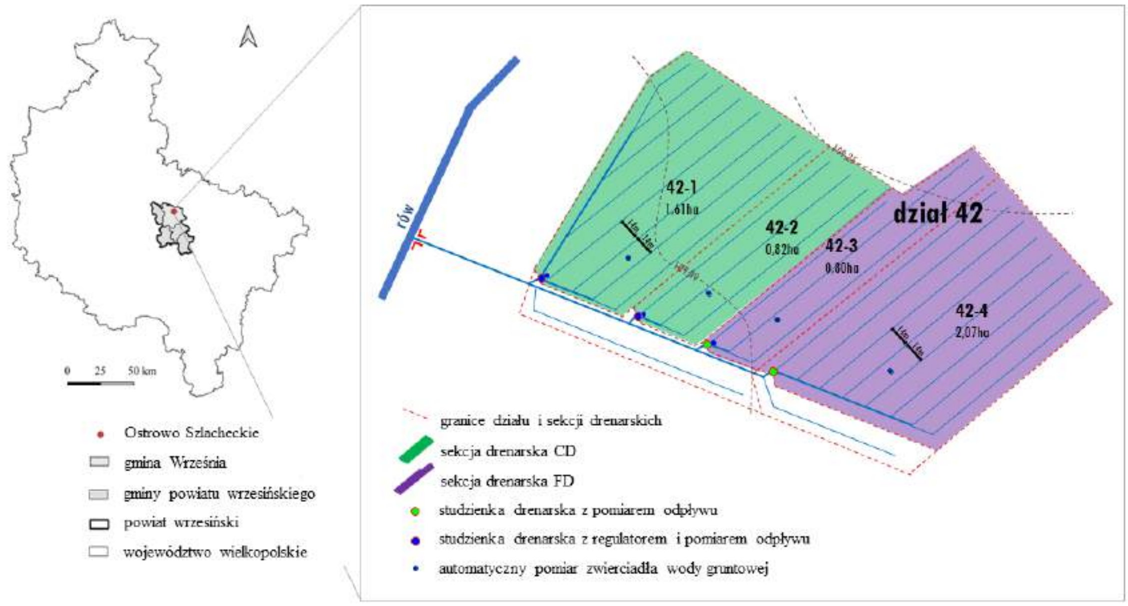
W każdym artykule (P1, P2 i P3) składającym się na niniejszą rozprawę doktorską przedstawiono szczegółowy opis wykorzystanych materiałów i przyjętej metodyki w celu weryfikacji przyjętych hipotez badawczych. Poniżej na rycinie 1, wskazano zastosowany schemat działań podjętych przy realizacji zbioru artykułów naukowych.



Ryc. 1. Schemat realizacji zbioru trzech spójnych tematycznie artykułów

3.1. Charakterystyka obiektu badań

Badania prowadzono na obiekcie drenarskim „Ostrowo Szlacheckie" położonym w gminie Września, w powiecie wrzesińskim, w województwie wielkopolskim. Zgodnie z położeniem fizycznogeograficznym znajduje się on w makroregionie Pojezierze Wielkopolskie, w mezoregionie Równina Wrzesińska. Pod względem hydrograficznym obiekt położony jest na obszarze dorzecza Odry, w regionie wodnym Warty, w zlewni bilansowej Warta od Neru do Prosny, w zlewni JCWP rzecznej Rudnik o kodzie RW6000091836869, będącej typem potoku lub strumienia nizinnego. Cały obiekt drenarski zajmuje powierzchnię 107 ha. Do badań szczegółowych wykorzystano eksperymentalny dział drenarski 42, o sumarycznej powierzchni 5,3 ha. Sekcje drenarskie 42-1 i 42-2 stanowiły obszary z zainstalowanymi prototypami urządzeń do stosowania CD, zaś dwie pozostałe sekcje 42-3 i 42-4 stanowiły obszary z FD (ryc. 2). Do obliczeń przyjęto występującą na tym obszarze rozstawę drenów wynoszącą 14 m i głębokość drenowania 0,90 m p.p.t. Obiekt został wykonany w technologii bezrowkowej z rur PVC, prace wykonawcze realizowano na początku lat 80. XX wieku. Ponadto dokładna charakterystyka obiektu badań została przedstawiona w publikacjach P2 i P3.



Ryc. 2. Położenie administracyjne obiektu badań i schemat działu drenarskiego 42

3.2. Badania i pomiary terenowe

Dane meteorologiczne rejestrowano od listopada 2018 roku, w tym sumę opadów i temperaturę powietrza z częstotliwością odczytu co 10 minut. Stacja zlokalizowana była w Sokołowie oddalonym o 3,5 km od obiektu badań.

W październiku 2019 roku wykonano polowe badania gleboznawcze w celu określenia zmienności gleb metodą punktów rozproszonych. Po wybraniu lokalizacji pedonów reprezentatywnych wykonano w każdej sekcji drenarskiej po jednej odkrywce, wraz z szczegółowym opisem morfologii profili glebowych. Pobrano z każdego poziomu próbki gleby o strukturze naruszonej i nienaruszonej do analiz laboratoryjnych właściwości fizycznych, chemicznych, hydraulicznych i zdolności retencyjnych.

Prowadzono ciągłe i telemetryczne pomiary głębokości zalegania zwierciadła wód gruntowych, przy wykorzystaniu urządzeń Levelogger i Barologger firmy Solinst w latach 2019-2020. Również weryfikowano ręcznie pomiary poziomu wód gruntowych w piezometrach przy użyciu świstawki hydrogeologicznej Solinst Model 101.

W trakcie kampanii pomiarowych, prowadzonych w okresie luty-marzec-kwiecień 2019 roku wykonywano systematyczne pomiary natężenia odpływów z sieci drenarskiej. Ponadto dokonywano poborów próbek wody z odpływów drenarskich z częstotliwością dwa razy w tygodniu w okresie ich występowania.

Dokładniejsza charakterystyka wykonanych badań i pomiarów terenowych została opisana w publikacjach P2 i P3.

3.3. Analizy fizyko-chemiczne gleb i odpływów drenarskich

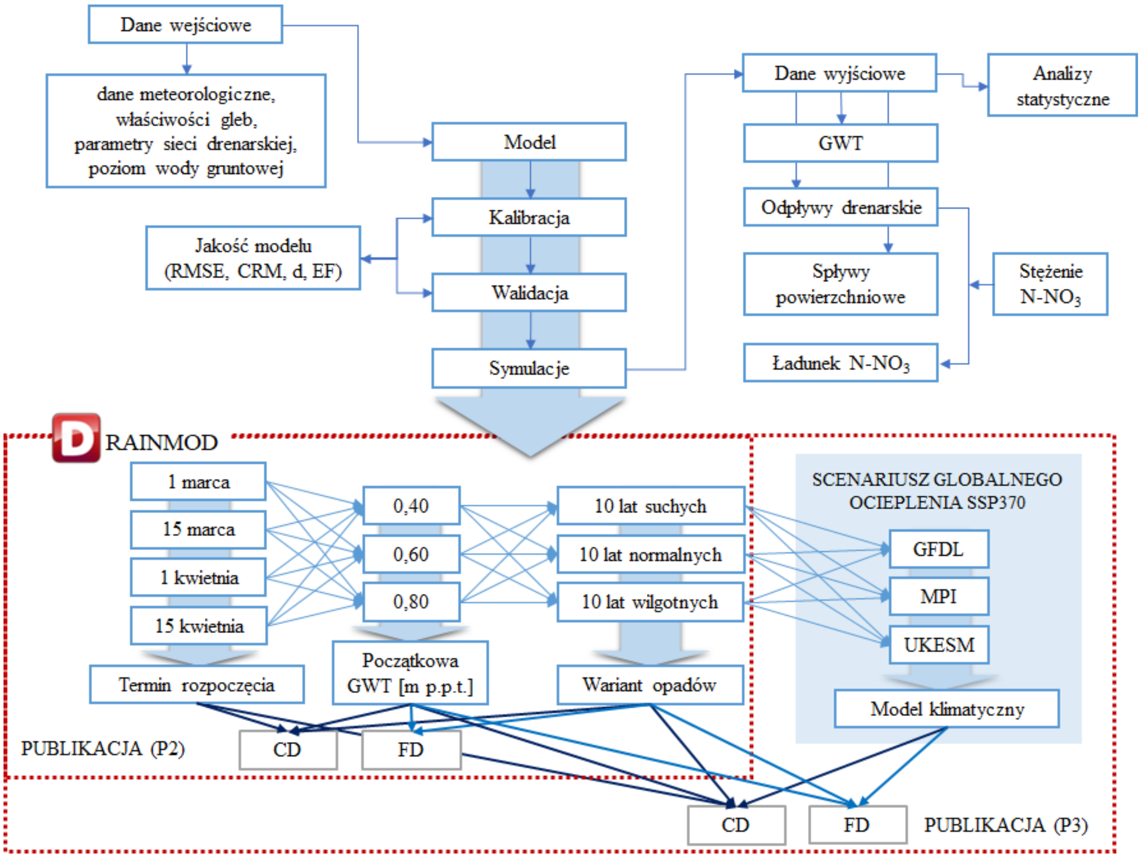
Laboratoryjne badania właściwości fizyko-chemicznych gleb obejmowały wykonanie następujących analiz: gęstości objętościowej za pomocą oznaczania w cylinderkach o objętości 100 cm^3, gęstości fazy stałej gleb metodą piknometryczną, składu granulometrycznego metodą areometryczną w modyfikacji Prószyńskiego i metodą sitową, odczynu (pH) metodą potencjometryczną w H_2O i KCl, przewodnictwa elektrolitycznego (EC), zawartości $CaCO_3$ metodą Scheiblera, zawartości Corg metodą suchej mineralizacji za pomocą analizatora N/C 3100 JenaAnalytik, saturacyjnej przewodności hydraulicznej (ks) metodą stałego spadu hydraulicznego, uwilgotnienia powierzchniowego poziomów gleb metodą suszarkowo-wagową. Ponadto wykonano krzywe wodnej retencyjności z następującym uwzględnieniem: do 1 bara metodą komór ciśnieniowych Richardsa, a w zakresie niskich potencjałów wody glebowej – metodą prężności pary wodnej nad roztworem kwasu siarkowego. Krzywe wodnej retencyjności gleb zostały przedstawione w postaci równania van Genuchtena (1980), a wartości parametrów tego równania optymalizowano z zastosowaniem programu RETC.

W pobranych próbkach odpływów drenarskich oznaczono zawartość: azotu całkowitego (N całkowity) metodą Kjeldahla z miareczkowym oznaczeniem końcowym, azotu azotanowego (V) ($N\text{-}NO_3^-$) metodą z salicynianem sodu w środowisku kwasu siarkowego (IV), azotu azotanowego (III) ($N\text{-}NO_2^-$) metodą z kwasem sulfanilowym w środowisku kwaśnym, azotu amonowego ($N\text{-}NH_4^+$) metodą Nesslera, fosforu całkowitego (P całkowity) metodą mineralizacji z nadsiarczanem amonu, fosforany (PO_4^{3-}) metodą molibdenianową z kwasem askorbinowym.

Badania wykonano w laboratoriach Katedry Melioracji, Kształtowania Środowiska i Gospodarki Przestrzennej oraz Katedry Gleboznawstwa, Rekultywacji i Geodezji według obowiązujących norm.

3.4. Model DRAINMOD

Na podstawie danych wejściowych charakteryzujących warunki termiczno-opadowe, glebowe i parametry sieci drenarskiej przygotowano model DRAINMOD (ryc. 3). Do procesu kalibracji i walidacji użyto danych poziomu zalegania wód gruntowych odpowiednio z okresu wegetacyjnego 2019 i 2020. Wyniki kalibracji i walidacji modelu DRAINMOD zamieszczono w pracach P2 i P3.



Ryc. 3. Schemat procedury modelowania i tworzenia wariantów symulacji CD i FD dla modelu DRAINMOD

Skalibrowany i zwalidowany model użyto do określenia możliwości zastosowania CD na podstawie danych meteorologicznych ze stacji Poznań-Ławica, ze względu na znaczące braki danych dla temperatury powietrza i sumy opadów dla najbliższych stacji Słupca i Września. W publikacji P2 przyjęto po 10 lat suchych, normalnych i mokrych, zgodnie z klasyfikacją Kaczorowskiej (1962) z wielolecia 1961-2020 udostępnionych przez IMGW-PIB. Natomiast do kolejnej publikacji (P3), bazując na danych historycznych, wybrano odpowiednio dane z modeli klimatycznych UKESM, MPI i GFDL dla scenariusza SSP370 najbliższej przyszłości (2021-2050). Analizy wykonywano dla okresu wegetacyjnego od 1 marca do 30 września. Ponadto w obu pracach (P2 i P3) przyjęto czynniki wpływające na efektywność CD takie jak: termin rozpoczęcia praktyki CD (1 marca, 15 marca, 1 kwietnia i 15 kwietnia), początkowa głębokość zalegania zwierciadła wód gruntowych (0,40 m, 0,60 m i 0,80 m p.p.t.) oraz wariant opadów rocznych (lata suche, normalne i mokre).

3.5. Analiza statystyczna wyników i obliczenia

Na podstawie wybranych zbiorów artykułów określono efekt jakim była różnica pomiędzy wielkością odpływów drenarskich i ładunkiem NO_3 przy zastosowaniu FD i CD. Do wykonania metaanaliz wykorzystano moduł „Metaanaliza i metaregresja" programu STATISTICA 13.3 zestawu analitycznego. Na wagę każdej publikacji w metaanalizie składało się 7 parametrów, tj. liczba lat, lokalizacji, ilość działów drenarskich, rozstawy i głębokości drenów, warianty CD i rodzaje gleb. Następnie wykonano analizę wrażliwości, niejednorodności wyników i metaanalizę w grupach. Na podstawie obliczonej wartości iloczynu wskazanych parametrów wyróżniono trzy grupy: grupa 1 od 1 do 10, grupa 2 od 10 do 100 i grupa 3 powyżej 100. Szczegółowa metodyka przeprowadzonych metaanaliz i innych związanych z nią analiz statystycznych przedstawiona została w pracy P1.

Na potrzeby oceny kalibracji i walidacji modelu DRAINMOD wykorzystano pierwiastek błędu średniokwadratowego (RMSE), współczynnik odchylenia resztkowego (CRM), wskaźnik zgodności (d) i efektywność modelu (EF). Wzory i objaśnienia współczynników i wskaźników przedstawiono w pracach P2 i P3.

Uzyskane wyniki poddano analizie statystycznej w celu wskazania istotnych różnic pomiędzy zastosowaniem CD a FD dla przyjętych parametrów tworzących różne warianty stosowanych metod drenowania. Zastosowano jednoczynnikową analizę wariancji (ANOVA) z testem Tukey'a w programie STATISTICA 13.3 (TIBCO Software Inc., Palo Alto, CA, USA).

4. Wybrane wyniki badań

W pierwszej publikacji (P1) wykonano systematyczny przegląd literatury wraz z metaanalizami dla określenia ogólnego efektu stosowania CD w aspekcie ilościowym i jakościowym. W przypadku metaanalizy w grupach, analiza wpływu CD na odpływ drenarski i wynoszenie ładunków NO_3 wykazały, że wyniki łącznego efektu dla drugiej i trzeciej grupy są istotne statystycznie, gdy przyjęto minimum 10 lat modelowania lub więcej. Należy zwrócić uwagę na indywidualność uzyskanych wyników, wynikającą ze zróżnicowania przyjętych pojedynczych badań, z różnymi danymi wejściowymi, będącymi konsekwencją charakterystyki sieci drenarskiej i warunków przestrzenno-czasowych. Metaanalizy w grupach wykazały także, że najważniejszym czynnikiem dla ważności uzyskanych wyników jest liczba lat przyjęta do modelowania.

Na podstawie wykonanych metaanaliz należy stwierdzić, że ogólny efekt stosowania CD pozwala na redukcję średnio 71 mm odpływów drenarskich i 8,36 kg NO_3 $ha^{-1} \cdot rok^{-1}$ w porównaniu do FD.

Głównym celem artykułu P2 było przedstawienie efektywności stosowania CD na podstawie pomierzonych, aktualnych i przeszłych warunkach meteorologicznych w skali obiektu Ostrowo Szlacheckie. Zgodnie z przyjętą metodyką dla różnych wariantów (ryc. 3) terminu rozpoczęcia CD, początkowego poziomu zwierciadła wody gruntowej przeprowadzono symulacje odpowiednio dla CD i FD, dla 30 lat z podziałem na lata suche, mokre i normalne. Efektywność stosowania CD, określono na podstawie zmian poziomu zwierciadła wód gruntowych (GWT) i ilości odpływów drenarskich. Przedstawiono także wielkość spływów powierzchniowych. Ponadto dla wskazania wpływu CD na wstrzymywanie wynoszenia $N\text{-}NO_3$ wraz z odpływem drenarskim wykorzystano ustalone na podstawie analiz chemicznych stężenie $N\text{-}NO_3$ z pobranych próbek odpływów drenarskich. Uzyskane wyniki w celu weryfikacji postawionych hipotez badawczych poddano opracowaniu statystycznemu.

Wyniki symulacji jednoznacznie wskazały, że rozpoczęcie stosowania praktyki CD w dniu 1 marca w porównaniu z późniejszymi terminami, istotnie wpływa na średnie wartości GWT przy jego różnym początkowym położeniu. W tym terminie rozpoczęcia CD wartości GWT były wyższe niż dla praktyki FD dla lat suchych, mokrych i normalnych. Najpłytsze położenie GWT stwierdzono dla terminu 1 marca dla wariantu początkowego 40 cm p.p.t. i wyniosły one średnio 117 cm p.p.t. dla lat mokrych. Okresy zalegania GWT powyżej poziomu zalegania sączków wyniosły 47, 56 i 55 dni odpowiednio dla lat suchych, mokrych i normalnych.

Rozpoczęcie wstrzymywania odpływów drenarskich dwa tygodnie później (15 marca) pozwala na zmniejszenie wielkości odpływów drenarskich do 40% w analizowanych wariantach. Późniejsze rozpoczęcie CD (1 i 15 kwietnia) skutkuje zbliżonymi lub identycznymi wynikami jak dla praktyki FD, co wskazuje na niską skuteczność CD w tych terminach. Rozpoczęcie praktyki CD dla wszystkich wariantów w dniu 1 marca powoduje wstrzymanie odpływów drenarskich z obiektu i ich redukcję o 100%. Ponadto w pracy P2 wykazano bardzo niewielkie zwiększenie spływów powierzchniowych dla CD w latach suchych, mokrych i normalnych, w analizowanym płaskim terenie o spadkach w zakresie 3-5‰.

Dla wskazanych wariantów symulacji modelowania CD w latach suchych, mokrych i normalnych rozpoczętych 1 marca wykazano całkowitą redukcję strat $N\text{-}NO_3$ w porównaniu do FD. Przewidywana redukcja wynosi od 6,22 do 21,71 $kg \cdot ha^{-1}$. Późniejszy termin 15 marca pozwala na redukcję o 10-17%, 19-37% i 12-25% wynoszonego biogenu odpowiednio w latach suchych, mokrych i normalnych. W skali całego obiektu drenarskiego przy rozpoczęciu CD w terminie 1 marca możliwe jest znaczące zmniejszenie wynoszenia ładunku $N\text{-}NO_3$ z 2363 do 48 kg dla początkowej głębokości GWT 40 cm p.p.t. w latach mokrych. W przypadku wstrzymywania odpływu praktyką CD w terminach 1 i 15 kwietnia wartości wynoszonego ładunku są zbliżone do praktyki FD.

Powyższe wyniki wskazują, że termin rozpoczęcia praktyki CD jest jednym z kluczowych elementów decydujących o jej skuteczności redukcji odpływów drenarskich w aspekcie ilościowym i jakościowym.

W trzeciej publikacji (P3) zastosowano model DRAINMOD z wykorzystaniem wcześniejszych wariantów CD, natomiast zmieniono parametr dotyczący danych meteorologicznych, uwzględniając ich przyszły scenariusz SSP370, który pozyskano z repozytorium danych ISIMIP3b dla czterech modeli GFDL, UKESM i MPI. Głównym celem tego artykułu było wskazanie jakich zmian można spodziewać się w bliskiej przyszłości przy stosowaniu CD w skali wybranego obiektu badań.

Wykonane symulacje modelowania, podobnie jak w pracy P2, wskazały, że termin rozpoczęcia praktyki CD 1 marca wpłynie na wyraźne podniesienie głębokości zalegania GWT. Na podstawie danych z modelu GFDL wykazano podniesienie GWT o średnio 27-41, 12-33 i 11-31 cm zaś dla modelu UKESM 14-34, 17-33 i 8-29 cm odpowiednio dla lat mokrych, normalnych i suchych w porównaniu do FD. W przypadku modelu MPI podobne wyniki uzyskano przy rozpoczęciu stosowania CD w terminach 1 i 15 marca, gdzie średnio GWT podniesie się o 23-39, 19-36 i 16-35 cm, odpowiednio w latach mokrych, normalnych i suchych. Pozostałe terminy nie wpłyną znacząco na podniesienie GWT. Ponadto wskazano, że w latach mokrych dla początkowej głębokości 40 cm p.p.t. poziom GWT powyżej sączków będzie utrzymywał się przez 67, 64 i 60 dni odpowiednio dla modeli GFDL, MPI i UKESM. Natomiast dla głębokości 60 cm p.p.t. wynosić będzie średnio 63, 60 i 53 dni dla GFDL, MPI i UKESM, zaś dla 80 cm p.p.t. poniżej 54 dni dla wszystkich modeli.

Wstrzymanie odpływów drenarskich przy zastosowaniu CD w terminie 1 marca pozwoli na 100% zablokowanie odpływów w porównaniu do FD dla wszystkich modeli, co jest wynikiem niemal identycznym jaki uzyskano w pracy P2. Późniejszy termin 15 marca pozwoli na osiągnięcie ponad 85% wstrzymania odpływów (model MPI). W latach mokrych odpływ drenarski będzie występował średnio przez 17-19, 18-21 i 15 dni dla modeli GFDL, MPI i UKESM. W pozostałych wariantach CD dla lat normalnych i suchych liczba dni będzie mniejsza. Wpłynie to na wzrost wielkości i formowanie się spływu powierzchniowego w bliskiej przyszłości. Najwyższą wartość spływu powierzchniowego (powyżej 30 mm) określono dla rozpoczęcia CD w terminie 1 marca w latach mokrych dla modelu GFDL. W latach normalnych dla modeli GFDL i UKESM, dla zakładanych wariantów symulacji, określono spływy powierzchniowe średnio jako 25 mm z wyjątkiem terminu 1 marca. W przypadku lat suchych dla wszystkich modeli odnotowano najniższe wartości spływu. Wyniki wskazują, że w bliskiej przyszłości (2021-2050) stosowanie CD może powodować większe spływy powierzchniowe w porównaniu do aktualnych warunków meteorologicznych dla analizowanego obiektu.

Wstrzymywanie odpływów drenarskich w terminie 1 marca spowoduje redukcję wynoszonych ładunków $N\text{-}NO_3$ o ponad 95% w porównaniu do FD dla wszystkich wariantów, dla trzech modeli klimatycznych. Średnia wielkość zmniejszenia ładunków wyniesie 24, 22 i 19 $kg \cdot ha^{-1}$ w latach mokrych dla modeli GFDL, MPI i UKESM. W latach normalnych i suchych można spodziewać się niższych wartości wstrzymywania wynoszonych ładunków.

5. Wnioski

Na podstawie przeprowadzonej metaanalizy, wykonanych pomiarów oraz wyników symulacji dotyczących efektywności stosowania kontrolowanego odpływu (CD) na ograniczenie odpływów drenarskich w aspekcie ilościowym i jakościowym, sformułowano następujące wnioski:

1. Metaanaliza danych literaturowych wskazuje, że stosowanie praktyki CD pozwala na zredukowanie wielkości odpływu drenarskiego średnio o 30,5% i zmniejszenie ładunku NO_3 o 33,61% w stosunku do odpływu swobodnego (FD).
2. W warunkach klimatyczno-glebowych środkowej Wielkopolski istotny wpływ na redukcję odpływu drenarskiego ma termin rozpoczęcia stosowania CD. Rozpoczęcie praktyki CD w pierwszych dwóch tygodniach marca powoduje zmniejszenie ilości odpływów drenarskich zarówno dla symulacji wykonanych dla danych historycznych i bliskiej przyszłości.
3. Przyjęty przyszły scenariusz zmian klimatycznych SSP370 wykazuje jednoznacznie na wzrost ilości odpływów drenarskich przy zastosowaniu drenowania konwencjonalnego (FD) w latach mokrych dla wszystkich modeli klimatycznych.
4. Stosowanie CD wpływa na podniesienie średniej głębokości zalegania wód gruntowych (GWT) w porównaniu do FD. Przeprowadzone symulacje wskazują na wydłużenie czasu utrzymywania się GWT powyżej poziomu ułożenia sączków drenarskich w bliskiej przyszłości, w porównaniu z wynikami uzyskanymi dla aktualnych warunków meteorologicznych.
5. Wykazano istotne zwiększenie ilości spływów powierzchniowych w najbliższej przyszłości w porównaniu do symulacji dla danych aktualnych. Może to wynikać ze spodziewanego zwiększenia częstotliwości występowania opadów nawalnych.
6. Efektywność redukcji ładunku $N\text{-}NO_3$ wynoszonego z odpływem drenarskim przy zastosowaniu CD jest największa w latach mokrych, dla obserwowanych warunków meteorologicznych i przyszłych scenariuszy klimatycznych.

Bardziej szczegółowe wnioski zostały wskazane w opublikowanych artykułach stanowiących część niniejszej rozprawy doktorskiej, a które są dołączone w punkcie 8 niniejszego autoreferatu.

6. Podsumowanie

Niniejsza dysertacja dotyczy jednego z aktualnych wyzwań przed jakim stoi polskie rolnictwo w perspektywie zmiany ilości dostępności wód i deficytu wody do produkcji roślinnej. Realizacja następującej rozprawy doktorskiej może wnieść istotny wkład do dziedziny nauk inżynieryjno-technicznych i dyscypliny inżynieria środowiska, górnictwo i energetyka poprzez zwiększenie stanu wiedzy o stosowaniu CD na obiekcie drenarskim i stanowić przyczynek do podjęcia szerszych badań, także terenowych, w tym zakresie. Zastosowanie połączenia badań terenowych i modelowania pozwala na określenie rezultatów stosowania CD w różnych scenariuszach i projekcjach zmian klimatycznych

W ujęciu społecznym wyniki pracy pozwolą na zmianę postrzegania drenowań jako melioracji działających w sposób jednostronny – odwadniający. Pozwoli to „nadać drugie życie” i często wykorzystać istniejącą infrastrukturę drenarską lub wprowadzić nową, zaprojektowaną z uwzględnieniem możliwości stosowania CD. Jest to jedno z pierwszych naukowych przedsięwzięć, mające na celu wypracowanie praktycznych wskazówek stosowania CD w Polsce. Może to w przyszłości przyczynić się do stworzenia skutecznych i zrównoważonych systemów odwadniających, wpływających pozytywnie na bilans wodny w skali pola. Jest to także rozwiązanie ekoinżynieryjno-techniczne pozwalające na istotną poprawę jakości wód, co jest odpowiedzią na rosnącą świadomość obywateli dla poszukiwania rozwiązań przyjaznych środowisku.

W kontekście uzyskanych wyników należy wspomnieć o uwarunkowaniach termiczno-opadowych dla stacji meteorologicznej Sokołowo zainstalowanej w ramach projektu INOMEL. Wpływ na wyniki wykonanych symulacji miały pomiary warunków meteorologicznych prowadzone w latach 2019-2020, w których średnia temperatura powietrza dla okresu wegetacyjnego wynosiła odpowiednio 15,2°C i 14,1°C oraz średnia suma opadów wynosiła 306 mm i 337 mm. W przypadku innych obiektów uzyskane wyniki mogą różnić się, z uwagi na inne uwarunkowania klimatyczne.

Zastosowanie kontrolowanego odpływu w praktyce wymaga dalszych badań i ich rozszerzenia o badania terenowe, prowadzone na różnych obiektach, o innych parametrach glebowych i warunkach klimatycznych. Ponadto można rozszerzyć badania o zastosowanie CD we współpracy z nawadnianiem deszczownianym czy wykorzystaniem recyklingu odpływów drenarskich. Konieczne jest także prowadzenie takich badań w aspekcie ich wpływu na wielkości uzyskiwanych plonów, co będzie niezwykle istotne dla rolników gospodarujących na polach, wyposażonych w systemy kontroli odpływów drenarskich.

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8. Wykaz artykułów naukowych wchodzących w skład rozprawy doktorskiej

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PLOS ONE

RESEARCH ARTICLE

Effects of modelling studies on controlled drainage in agricultural land on reduction of outflow and nitrate losses–a meta-analysis

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Abstract

A review with meta-analysis of outflow and nitrate loss reduction in controlled drainage (CD) vs conventional, free drainage (FD) was carried out in the study. Since the results of experimental field studies usually cover short periods of data collection, hence in this paper, meta-analyses were based on model studies that usually cover a longer time range. The databases Web of Science and Scopus were searched for eligible English articles, published until December 2020, that describe the quantity and quality of drainage water. The meta-analysis of outflow and nitrate loss reduction in CD vs FD using the mean difference (MD) with a confidence interval (CI) of 95%. The influence of each study was measured through heterogeneity, sensitivity analyses and publication bias using STATISTICA (version 13.3) for all analyses. Of the 107 works identified, 18 were finally included in the analysis based on established criteria required for an appropriate meta-analysis. In general the results indicate a reduction in average drainage outflow of 30.5% (MD = -71.26 mm; 95% CI, -103.49 —-39.04; p = 0.000) in arable land with CD in comparison to FD practice. In the case of nitrate load the reduction was 33.61% and in the drainage water there was lower content in CD practice by an average of 8.36 kg NO_3 $ha^{-1}year^{-1}$ (95% CI, -9.93 —-6.79; p = 0.000). Subgroup analysis of two meta-analyses indicates that the results concerning these associations may vary with the calculated weight for each article, in which the number of years of study had the most significant impact.

Introduction

Drainage systems, comprising ditches or subsurface drains, are important for agricultural production of the world's cropland. Subsurface tile drainage, i.e. free drainage (FD), is widely practiced in productive agricultural land with poorly drained soils in different parts of the world [1–3]. Benefits of this management practice are increased crop productivity and improved economic returns for crop producers. The consequences of drainage water from drainage network systems have been identified as an important factor contributing to increasing nutrient loads,

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mainly nitrate-nitrogen (NO_3^-−N), NH_4^+−N, total nitrogen (TN) and total phosphorus (TP) into surface receiving waters [4–6]. Globally, it is estimated that the losses of NO_3^- from agricultural systems account for 19% of the total amount of N used worldwide [7].

Tile drainage plays a significant role in soil nitrogen losses from agricultural lands, thus affecting surface and groundwater and leading to deterioration of water quality, especially as pollutants originating from agricultural drainage outflow include sediment, nitrogen and also phosphorus, pesticides, pathogens, salts, trace elements, and dissolved organic carbon [8–13]. This threatens the hydrological environment due to the accumulation of nitrates in water sources and oxygen deficiency [14–16]. This is confirmed by long-term studies carried out in various catchment areas, which indicate that agricultural systems affect nitrate levels in river waters. The research concerns facilities located in other climatic zones, soil properties and different cultivation systems, which allows a greater understanding of nitrate losses to subsurface drainage [17, 18]. This is a particularly important issue from the point of view of the environmental risk related to nitrate losses from agricultural sources. Several management practices have been developed to reduce the nitrate loading from artificially drained agricultural areas, including controlled drainage (CD), controlled tile drainage (CDT), drainage water management (DWM) [19–22], denitrifying bioreactors (DBR) [23–25], free water surface flow constructed wetlands (FWS) [26–28], saturated buffer zones (SBZ) and integrated buffer zones (IBZ) [29–31], and drainage water recycling [32].

CD is a conservation practice, to artificially raise and adjust the level to which the water table in a tile-drained field is allowed to rise, using a water control structure near the outlet of a drain to adjust the effective outlet elevation. Also, it can reduce nutrient loss during wet periods by storing more water in the field. This drainage water management affects the hydrological changes in the field cycle, which, depending on the location and weather conditions, increases some or all of the following flow components: root zone water storage, seepage, surface drainage, plant uptake and evaporation [33, 34]. Another benefit is reducing losses of nitrogen (N) from agricultural subsurface drained fields to surface waters. The consequence is an increase in groundwater levels, and longer anaerobic conditions are created in the soil, ideal for denitrification [35–37]. This process involves microbial respiration under anaerobic conditions in which nitrates from the ecosystem return reactive nitrogen (Nr) to the atmosphere as N_2 and N_2O emissions [38]. This practice is one of the mitigation measures targeting nutrient losses from agricultural drainage systems' water before it enters streams [39].

Most of the research related to CD practice has been tested and widely used in US and Canadian studies for more than two decades [35, 36]. DWM is gaining popularity in other countries of the world due to improved quality of water flowing from drained agricultural fields to surface water. The practice has been tested on research facilities in several countries including Lithuania [40], Sweden [41], Denmark [39], Italy [42], China [43, 44], Iran [45], India [46], Japan [47], and Egypt [48]. Unfortunately, the results of experimental field studies usually include a short measurement period of CD effectiveness. Therefore, on the basis of these measurements, model studies covering a longer time range are carried out.

Among the many studies on the influence of CD on the drainage water quality and quantity, there are disparities in the obtained results. Some of them show a positive effect while others show a negative or no effect of CD on the quantity and quality of drainage water. Hence, in order to comprehensively analyze the effect of CD on the quantity and quality of drainage water, which will be statistically confirmed at the same time, a meta-analysis can be used, especially since there are no such studies. Increasing the implementation of the practice provides more data measured from field studies, and modelled data assessing the impact of CD on the quantity and quality of water in the discharge of tiles from fields or small catchment areas.

One of the soil-specific models used to support tile drainage research is DRAINMOD created by Skaggs et al. [34, 49, 50, 51]. DRAINMOD is one of the most widely used hydrologic models to simulate subsurface drainage systems. It simulates surface runoff, infiltration, evapotranspiration, subsurface drainage and seepage from the soil profile in response to given climatological conditions, crop rotation, soil type, and drainage system parameters and management [34]. The program is used to simulate the water table depth, drained outflow or nitrate-nitrogen in the drainage water of drained soils in different parts of the world, for present, future and past data. In addition, there are several models to assess the long-term impact of agricultural management and climate change on crop production and water quality [52]. In recent decades, the ability of water quality models in the root zone to study the impact of agricultural management practices on water quality and crop growth in places significantly different in terms of climatic and pedological conditions has been widely created and improved.

Due to the shortage of previous studies comprehensively analyzing model data on the effect of CD on the quantity and quality of drainage water, including statistical validation, we applied a meta-analysis for this purpose. In this study, we focused on comparing the results obtained for DRAINMOD model studies under CD vs FD conditions and its effect on reduction of outflow and nitrate losses of drained agricultural land. Therefore, we used meta-analyses to synthetically and also statistically indicate the effectiveness of CD use in quantitative and qualitative aspects of drainage outflow.

Materials and methods

Search strategy

This meta-analysis was conducted (18 January 2021) by an advanced search in the *Web of Science* (WoS) by the *ISI Web of Knowledge* published by Thomson Reuters and Scopus; the owner of the database is Elsevier. The search scope was developed using the symbol "*" and the advanced search was performed for words or instructions created by logical operators. Keywords searched included ("controlled drainage" AND "drainmod") until December 31, 2020. The scientific documents are included in the database Web of Science Core Collection: *Science Citation Index Expanded* (*SCI-EXPANDED*). The meta-analysis was limited to articles published in English.

Inclusion and exclusion criteria

For further analysis, several articles were rejected after an initial review of the summaries and titles. A model study was selected considering CD and FD and their impact on the amount of outflow and nitrogen loss from fields. Articles from field studies, as well as those which provided insufficient data to conduct reliable meta-analysis or were reproduced publications, were also excluded.

Data extraction

A standard protocol for obtaining data and information on the basis of which eligible articles were established was prepared after consultation. The data collected included the name of the article, the name of the first author, the year of publication, the amount of outflow, the loss of N, the number of years of modelling, and additionally the texture of the soil, the crop, the amount of annual rainfall, the average temperature, and depth and spacing of the drainage. Disputes regarding the eligibility of the article for meta-analysis were resolved through a group discussion. The information and data were entered in the standard Microsoft Excel data extraction form (S1 Data).

Weights for individual articles in meta-analysis

In comparison to field research modelling of CD and FD practices gives the possibility of analyzing many combinations of different tile drainage and soil parameters, weather conditions and future climate predictions as well as CD variants and so on. Hence the derived conclusions of model simulations after validations can result from greater amounts of data than those obtained from field research. Pooled mean difference weighting by a function of sample size was used in meta-analysis weights [53, 54]. The following calculation is the sample weight for an individual study:

$$W_i = \frac{n_{tx,i} \cdot n_{ctr,i}}{n_{tx,i} + n_{ctr,i}} \tag{1}$$

where $n_{tx,i}$ = total number of modelled variants of CD, $n_{ctr,i}$ = total number of modelled variants of FD. The number of variants *ntx*,*i* and *nctr*,*i*, represents the result of multiplying the number of: years, locations, experimental plots, drainage spacing, drainage depth, variants of CD application as well as soil types (S1 Data).

Data synthesis and analysis

On the basis of the data from each article, the average value of outflows and nitrogen losses for CD and FD were calculated according to the number of variants. A mean difference (MD) with a confidence interval (CI) of 95% was used as a standard for measuring the relationship between CD and FD. Statistical heterogeneity was assessed in studies using Q and I^2 and L'Abbé plots. Q is Cochran's heterogeneity statistic usually computed by summing the squared deviations of each study's estimate from the overall meta-analytic estimate, weighting each study's contribution in the meta-analysis. I^2 explains the percentage of total variation across studies that is due to heterogeneity rather than chance, and it is a helpful estimate to investigate the causes and type of heterogeneity. Based on the Q value, T^2 is determined, defined as the estimator of the variance of the actual effects [55, 56]. A cumulative meta-analysis was performed taking into account the chronological effect of individual studies on the calculated overall effect and the error in its estimation varying over time after accounting for subsequent publications. A sensitivity analysis was performed for the change in cumulative effect due to the exclusion from the meta-analysis of individual studies as this will change the standard error. Wherever the results were heterogeneous, a random-effects model was used in the meta-analysis. In this selected statistical model, we assumed that the true effect may vary depending on the study. We chose this variant because the studies differed significantly in depth and drainage spacing parameters, duration simulation, modelling accuracy, soil and climate context, and cultivated plant species used. Subgroup analyses were carried out for possible causes of heterogeneity. Integrated estimates and associated CI of 95% were evaluated using forest plots as visualizations. Publication bias was evaluated qualitatively using funnel plots, Egger regressions, and the Begg–Mazumdar correlation test [57, 58].

Values of $p < 0.05$ were considered as valid for heterogeneity tests. For statistical analyses, STATISTICA software (version 13.3), the Set Plus module with meta-analysis and meta-regression, was used.

Results

Selected articles

In an electronic search of the literature, 107 potential articles were identified; 43 were found in the WoS database and 64 articles in the Scopus database. Following the completion of the preliminary screening of abstracts and titles, 57 articles were excluded on the basis of the inclusion criteria (8 duplicate articles and 49 on the basis of unrelated titles and summaries) and 50 articles remained for a full review of the text. In the secondary study and after the full-text review, a further 32 articles were excluded; they were rejected due to missing information to create a meta-analysis data statement for outflows and nitrate losses. Ultimately, eighteen studies after these exclusions were selected for the final analysis (Fig 1).

Description of selected articles

The publications used in this meta-analysis were published between 1995 and 2020. Most of the articles were published in *Agricultural Water Management* (9 papers), *Transactions of the ASABE* (2 papers). One article each was published in 7 journals on the effects of CD on drainage water quantity and quality using DRAINMOD modeling results: *European Journal of Agronomy*, *Geoderma*, *Irrigation and Drainage*, *Journal of Environmental Quality*, *Journal of Soil and Water Conservation*, *Sustainability*, and *Transactions of the ASAE*. Of the selected articles, there are 10 (Skaggs et al. [59], Breve et al. [60], El-Sadek et al. [61], Ma et al. [52], Salazar et al. [62], Luo et al. [63], Skaggs et al. [64], Negm et al. [65], Negm et al. [66], Youssef et al. [67]) that are included in two meta-analyses of subsurface drainage outflow reduction and nitrate in drainage outflow loss. Subsequently, 4 publications (Skaggs et al. [68], Pease et al. [69], Sojka et al. [70], Singh et al. [71]) concerning outflows and 4 publications (Breve et al. [72], Singh et al. [73], Ale et al. [74], Ale et al. [75]) related to nitrogen losses were included in the relevant analyses. Most studies concern the modelling of outflows from research facilities located in the United States (83%), while the remaining 3 studies concern European countries: Belgium, Sweden and Poland (Fig 2). Table 1 presents the characteristics for selected articles regarding authors and year of publication, country, soil texture, years for which CD use was modelled, and depth and spacing of drains.

Weights for individual articles

Due to differences in the basic characteristics of meteorological, soil and drainage networks introduced into models in different selected articles, a weight was established for each article. There is a significant difference in the years of modelling drainage in articles, from 1 to 90 years; it affected in some cases the final value of the weight. In addition, in some cases, the final assessment was also influenced by significant values in other parameters such as locations (Youssef et al. [67]), plots (Ma et al. [52]), spacing (Breve et al. [72]), and soils (Ale et al. [75]). Luo et al. [63] modelled for different spacing, others to determine outflows and others to determine nitrate loss. The range of weights for accepted articles is from 1 to 630. Three articles have the smallest weight values (Breve et al. [60], Salazar et al. [62], Negm et al. [66]) whose value reflects the number of years used for modelling. The largest weight values are published (Luo et al. [63], Youssef et al. [67]) with the largest number of modelling years and more variants of other parameters. The values of N_{CD} and N_{FD} for selected articles were used to determine the number of meta-analyses performed for the reduction of outflow drains and nitrate losses with outflow.

Meta-analysis of drainage outflow and nitrate reduction

Two meta-analyses for subsurface drainage outflow reduction and nitrate in drainage water by CD versus FD were initially performed (Fig 3A and 3B). The first meta-analysis therefore used a random effect model to demonstrate how controlled drainage affects the reduction of drainage compared to conventional drainage. The overall effect from all articles analyzed indicates that the use of CD statistically significantly reduces drainage outflow by 71.26 mm per year. In

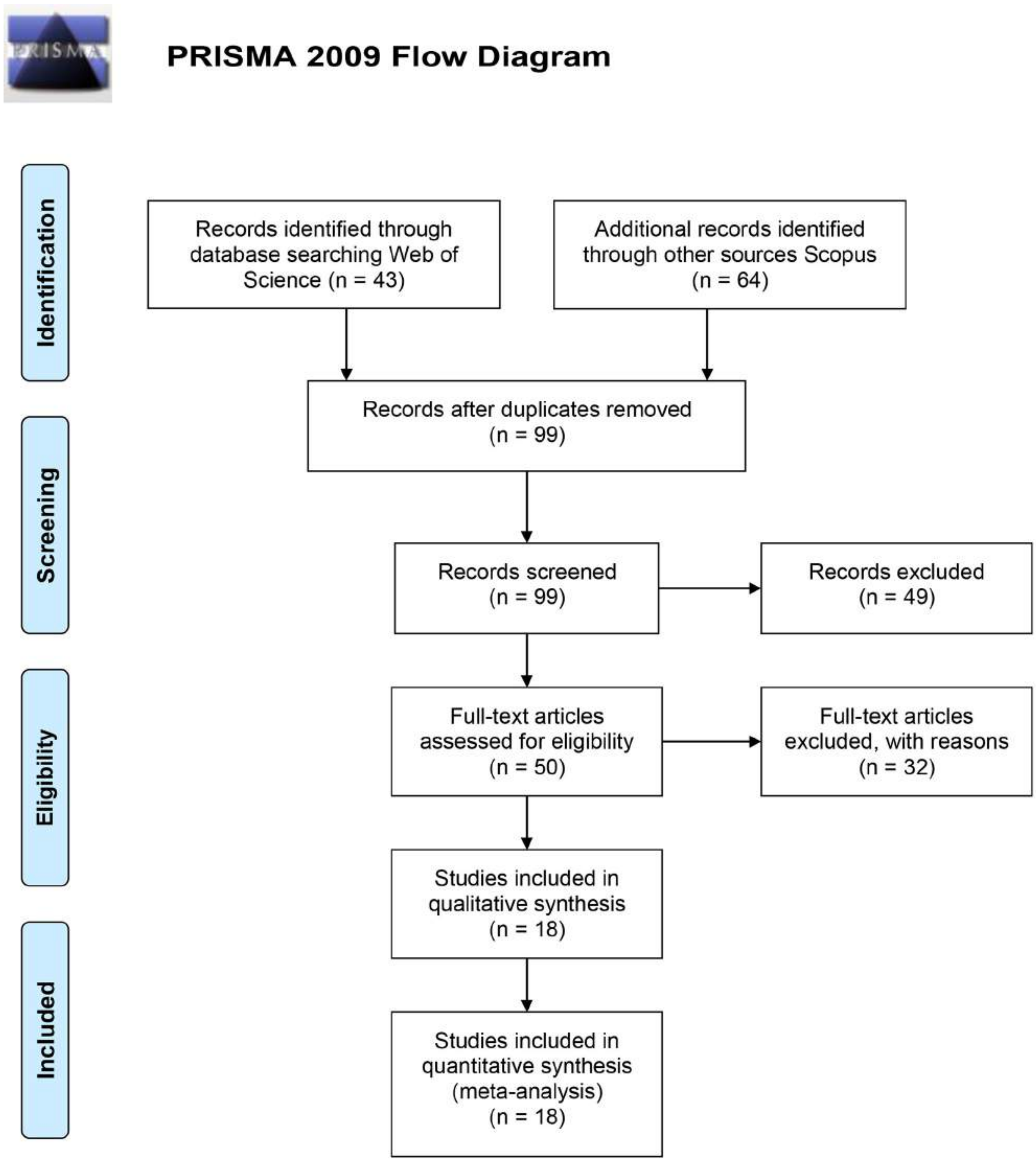

Fig 1. Flowchart of the literature search.

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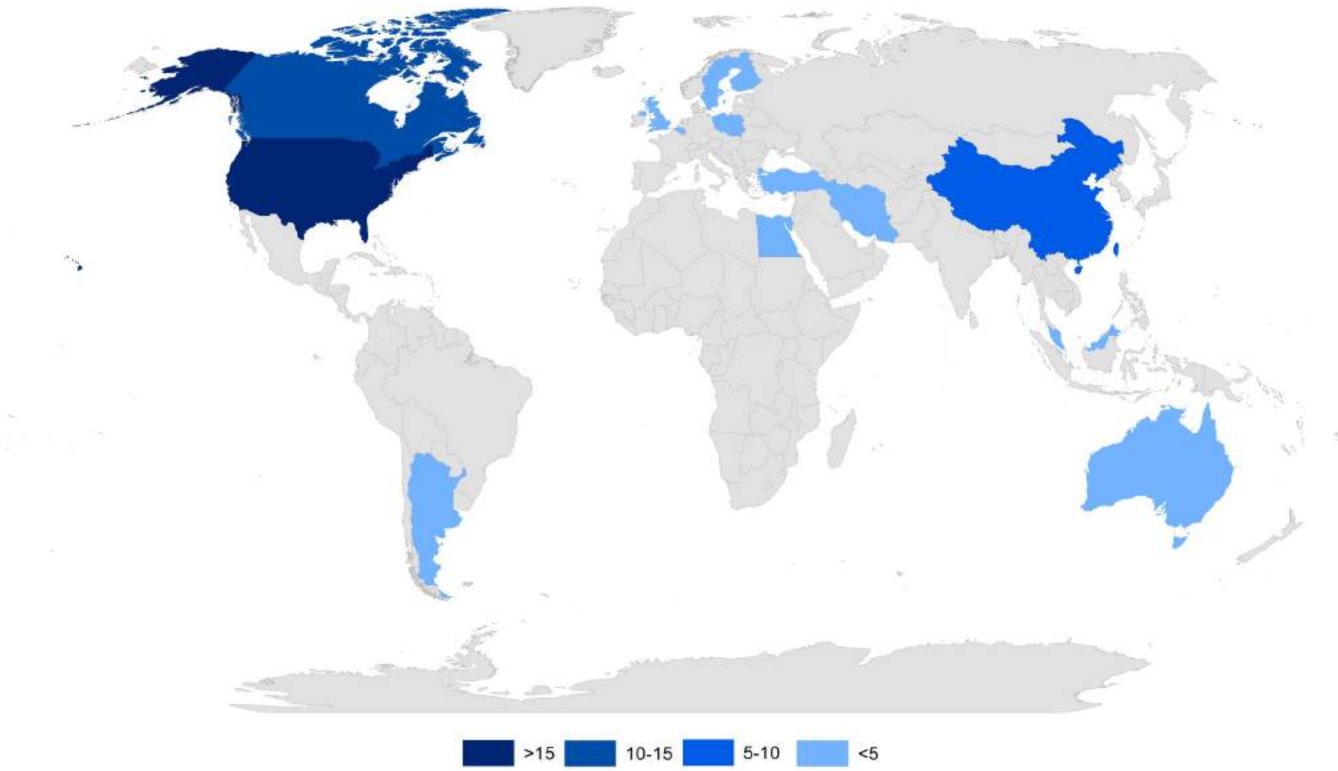

Fig 2. Countries to which the articles used in the record screening of articles relate.

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Table 1. Characteristics and information of studies evaluated in the meta-analysis.

Authors and date	Country	Soil texture	Years	Drain depth (m)	Drain spacing (m)
Skaggs et al. 1995 [59]	USA	sandy loam	13	1.00	10, 20, 30, 40, 50, 100
Breve et al. 1997 [60]	USA	sandy loam	2	1.25	23
Breve et al. 1998 [72]	USA	sandy loam	20	1.00	10, 15, 20, 25, 30, 40, 50, 100
El-Sadek et al. 2002 [61]	Belgium	sand	14	1.25	10, 25, 50, 100, 300
Ma et al. 2007 [52]	USA	loam	24	1.20	29
Singh et al. 2007 [71]	USA	silty clay loam	60	0.75, 1.20	10–50
Salazar et al. 2009 [62]	Sweden	loamy sand	3	0.99–0.83, 0.99–0.96	9
Luo et al. 2010 [63]	USA	silty clay	90	0.90, 1.20	9, 12, 15, 18, 24, 30, 36
Skaggs et al. 2010 [68]	USA	sandy loam	50	1.20	30
Ale et al. 2012 [74]	USA	clay loam	25	0.90, 1.20	12–25, 25–35, 35–45, 45–60, 60–80
Ale et al. 2012 [75]	USA	silty clay loam	10	0.90	10
Skaggs et al. 2012 [64]	USA	sandy loam, silty clay loam, clay loam	25	1.20, 1.25	30
Negm et al. 2016 [65]	USA	sandy loam	25	1.18	23
Negm et al. 2017 [66]	USA	silty clay loam, clay loam	1	1.30	36.5
Pease et al. 2017 [69]	USA	silty clay	30	1.14	10
Youssef et al. 2018 [67]	USA	loam	25	1.45	27.40
Sojka et al. 2019 [70]	Poland	sandy loam	3	0.90	7, 14
Singh et al. 2020 [73]	USA	silty clay loam	7	1.10	36.5

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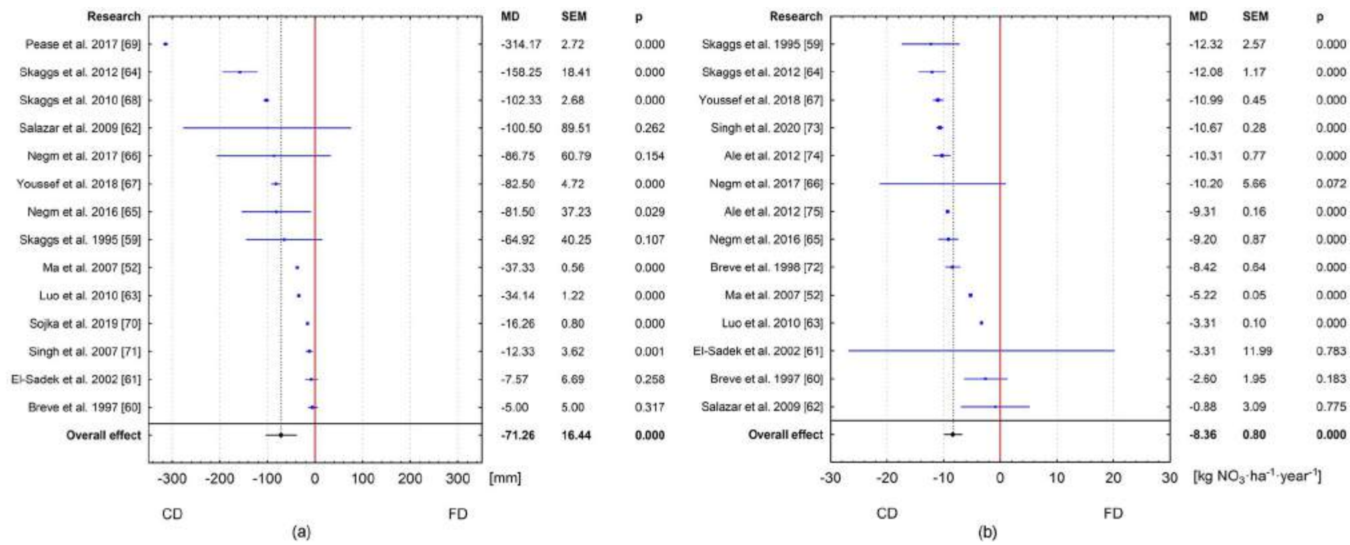

Fig 3. Meta-analysis for all articles: (a) subsurface drainage outflow reduction by CD versus FD; (b) reduction of nitrate load in drainage outflow by CD versus FD.

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absolute terms, this represents 30.5% of FD drainage outflow. All publications used in the meta-analysis indicated that the use of CD reduces outflow compared to FD. In this list, 5 publications were statistically insignificant (Fig 3A). Considering the year the study was published (Fig 4A), in the first period 1995–2007, when the first 5 publications were published, there was no statistically significant effect of CD on reducing drainage outflow. It is only with the inclusion of the 2009 study by Salazar et al. [62] that the effect was statistically significant and maintained after the inclusion of subsequent studies. Since this study, the 95% confidence intervals have narrowed significantly for the combined effect. The last 3 studies had high variability of results, which influenced the expansion of the 95% confidence interval for the combined effect.

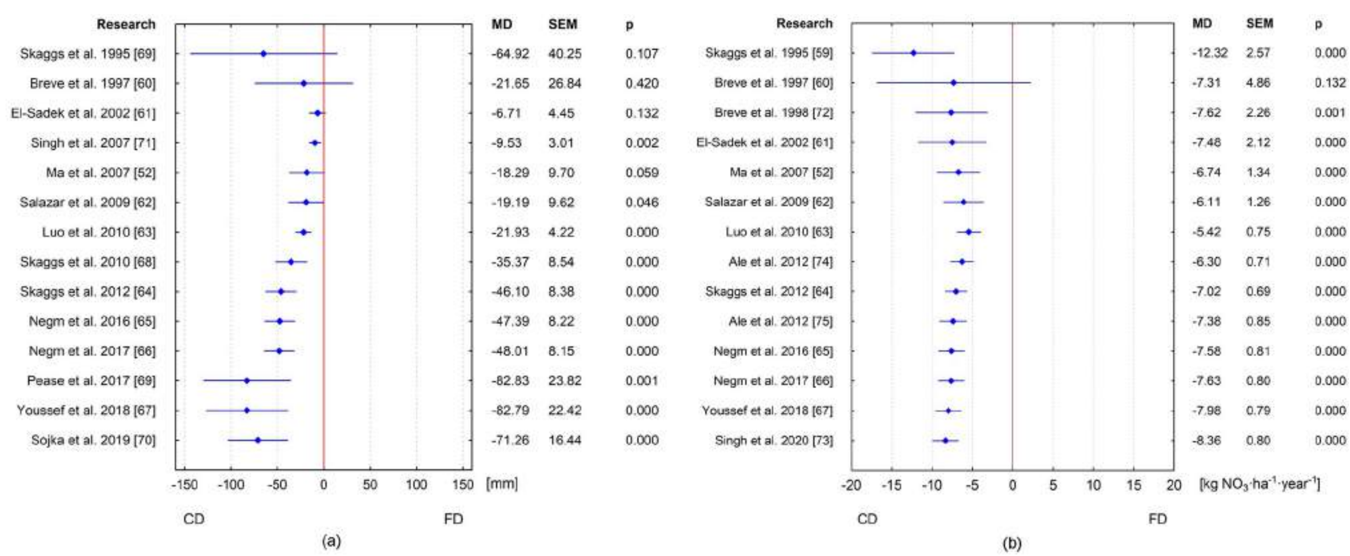

Fig 4. Cumulative meta-analysis: (a) subsurface drainage outflow reduction by CD versus FD; (b) reduction of nitrate load in drainage outflow by CD versus FD.

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The second meta-analysis also used a random-effects model to demonstrate how CD affects nitrate losses at low tide compared to FD. The findings of this analysis indicate a higher annual nitrate load in drainage waters in FD than in CD. The overall effect was statistically significant (Fig 3B) and showed an average reduction in nitrate losses of 8.36 kg NO_3·$ha^{-1}year^{-1}$ (MD = -8.36; 95% CI: -9.93 –-6.79, $p < 0.05$) and this represents 33.61% of nitrate FD outflow. It is also apparent that in 4 out of 14 studies the results were statistically insignificant. The results of the cumulative meta-analysis indicate that from 1995 [59], each addition of subsequent studies (except study [72]) had a statistically significant impact on the summary effect for the cumulative analysis (Fig 4B). In general, each further addition of a literature item resulted in a significant narrowing of the 95% confidence interval for the summary effect.

Based on the heterogeneity analysis (Fig 5A), there was significant variation between studies analyzing the effect of CD on drainage outflow reduction (I^2 = 99.89%; p = 0.000). The variance of T^2 effects was 3239.08 and represented 99.89% of the observed variability. The relationship between the drainage outflow effect in CD and FD practice modelling was shown in the L'Abbé plot (Fig 5A). The solid line corresponds to the equilibrium level (MD = 0.00) and the dashed line to the overall effect determined in the meta-analysis (MD = -71.26 mm). The size of the markers is proportional to the contribution of a given study to the meta-analysis. A significant dispersion of points around the dotted line indicates high variability in the results of the research. The results of the meta-analysis indicate a positive correlation between drainage outflow in FD versus CD. The most far removed from the cumulative effect of the meta-analysis is the publication by Peace et al. [69], indicating a significantly higher average outflow value for FD and at the same time the greatest reduction in drainage outflow using CD. In three literature items [60, 61, 70, 71], the results indicated a small effect of CD on outflow reduction, of which two results of items [60 and 61] were not statistically significant. The outcome of study

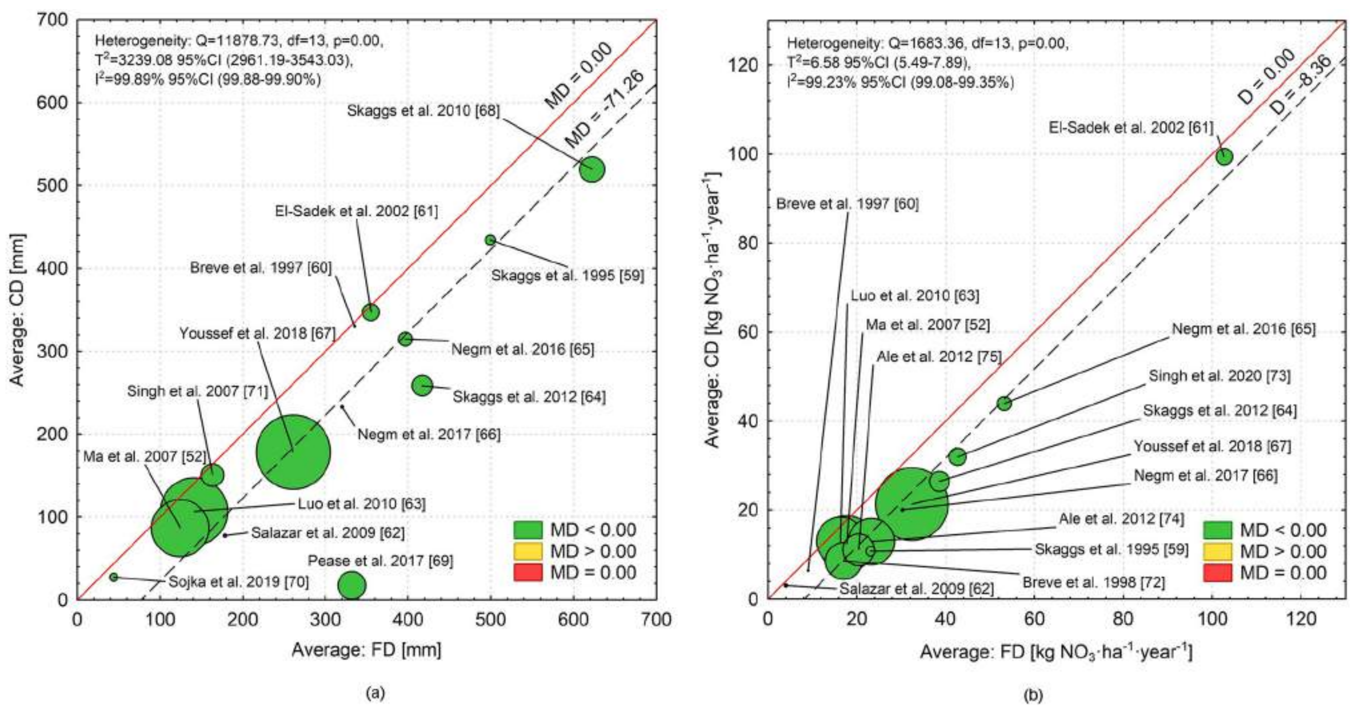

Fig 5. Heterogeneity analysis for all articles based on L'Abbé plot: (a) subsurface drainage outflow reduction by CD versus FD; (b) nitrate load in drainage outflow by CD versus FD.

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[68] is not much different from the combined effect of meta-analysis but has the largest drainage outflow values for both FD and CD. Analyzing the points (literature items except [69]) located within the solid and dashed lines, one can point out a certain regularity: the points are closer to the solid line the smaller the FD values are, while they move towards the dashed line as the FD increases.

Similarly, the results of the heterogeneity analysis were obtained for a meta-analysis of nitrogen losses, because Q is 1683.26 (df = 13) and the p value is less than 0.05. The variance of actual T^2 effects is equal to 6.58 and represents 99.23% of the observed variability (I^2 = 99.23%). In this case, the MD values of the individual tests are higher than the equilibrium level (MD = 0.00) (Fig 5B). In general, for nitrate in drainage outflow, the points (literature items) have less distribution around the dashed line than for water outflow. In addition, results from publications showing the lowest nitrate losses with both FD and CD were closer to the solid line (item [60, 62]), while those showing the highest nitrate losses with FD and CD (item [64, 65, 73]) were near the dashed line (except item [61]).

Sensitivity and subgroup meta-analysis

A meta-analysis of subsurface drainage outflow reduction in current studies and sensitivity analysis were also conducted. After the sequential removal of each study from the analysis, the average overall effect changed. Thus, it was found that the most significant impact on the results was from the research article by Pease et al. [69]. After its exclusion, we would get a slightly larger average effect (MD = -47.48 mm), and the standard error for the overall effect would decrease by about 60%. The article had a strong impact on the results of the meta-analysis. This was the study [69] with the largest absolute reduction in drainage outflow among the articles analyzed (MD = -314.17 mm).

Analyzed subgroups in the current meta-analysis take into account the number of years of model studies to minimize heterogeneity among different studies. Three groups are distinguished on the basis of the product of parameters used to calculate the weights of individual articles. The first includes studies up to 10 values of N_{CD} and N_{FD}, the second from 10 to 100, and the third above 100. Fig 6 shows the results of the analysis in such defined groups. The first group's overall effect score is statistically insignificant, MD = -75.90 mm (95% CI: -195.70–43.90; p = 0.331) and represents 33.73% of FD outflow. This group includes publications that analyzed the effect of CD on reducing drainage outflow for the fewest number of years. The final results of the overall effect for the second group, MD = -84.89 mm (95% CI: -123.73 –-46.05, p = 0.001) and the third, MD = -70.15 mm (95% CI: -75.23 –-65.08, p = 0.002) were statistically significant. These reductions represent 22.63% and 31.10% respectively. In addition, first and second groups contain publications (3 and 2, respectively) with an insignificant effect. When analyzing the forest plot for the distinguished groups the presented 95% confidence intervals for the group effect decrease from the first cluster to the third group. The closest to this effect is the D value of the third group, and from the selected articles the average difference between CD and FD for Youssef et al. [67] is 82.50 mm. The resulting total meta-analysis effect was most influenced by the three publications of Youssef et al. [67], Luo et al. [63] and Ma et al. [52], respectively 33.70%, 25.74% and 20.22%, in total explaining 79.66% of the results obtained. The smallest impact on the resulting total meta-analysis effect was found for the publications in the first group, two publications each of 0.11% and one of 0.06%. The most important in the first subgroup are two publications of 40% (Salazar et al. [62], Negm et al. [66]). The largest weights in the second subgroup are the two publications of Skaggs et al. [64] (37.88%) and El-Sadek et al. [61] (26.52%). In the third group, the three publications with

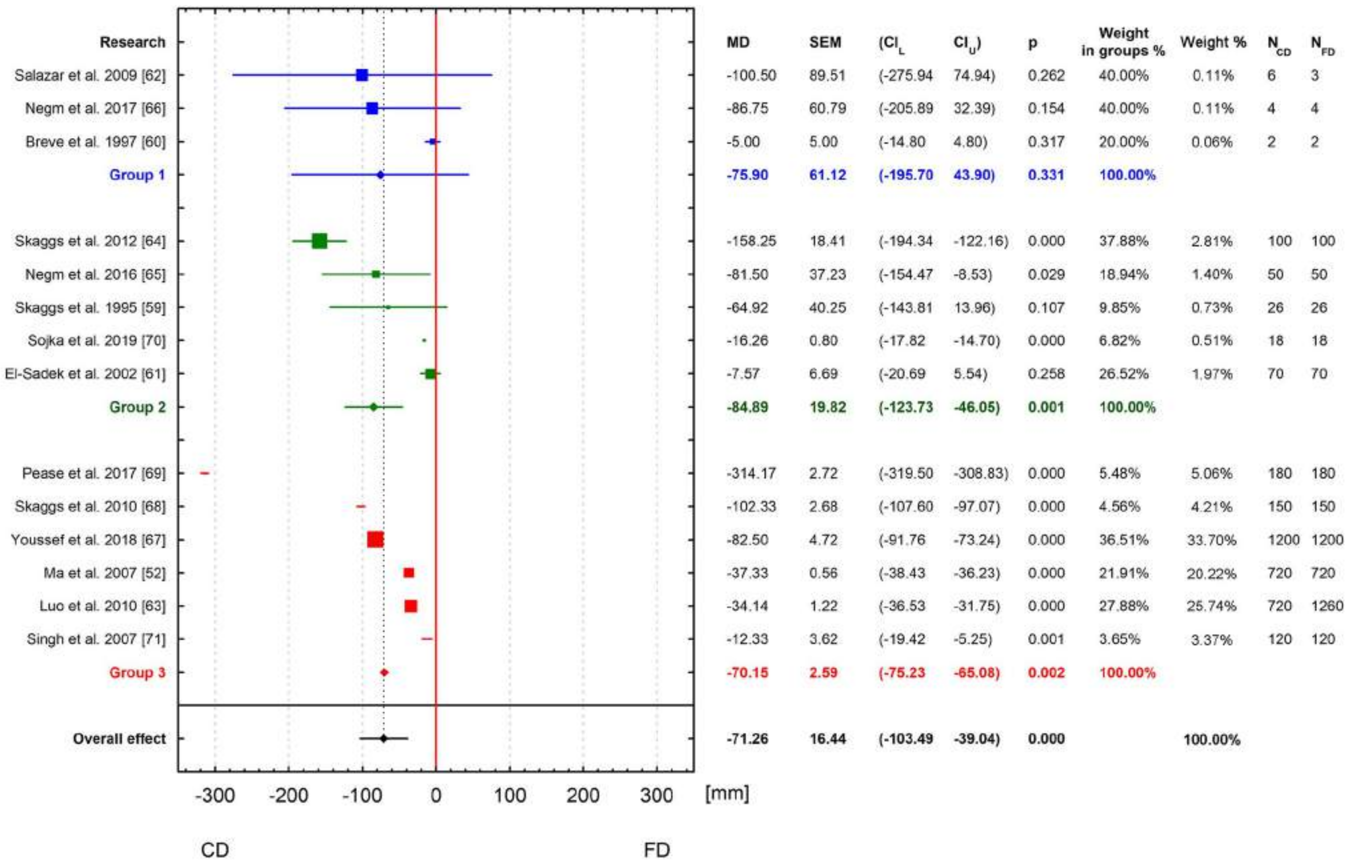

Fig 6. Meta-analysis in groups of subsurface drainage outflow reduction by CD versus FD.

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the highest weights are those of Youssef et al. [67], Luo et al. [63] and Ma et al. [52], respectively 36.51%, 27.88% and 21.91%.

Likewise, three article groups were distinguished when analyzing the effect of CD on nitrate load reductions (Fig 7). For the first group, the mean effect score is statistically insignificant, MD = -4.95 kg NO_3 $ha^{-1}year^{-1}$ (95% CI: -12.58–2.67; p = 0.096) representing a 28.18% reduction compared to FD. There was a statistically significant mean effect of CD practice on reduction of nitrate load for the second group, MD = -9.41 kg NO_3 $ha^{-1}year^{-1}$ (95% CI: -16.05 –-2.76, p = 0.000), and the third, MD = -8.27 kg NO_3 $ha^{-1}year^{-1}$ (95% CI: -8.98 –-7.56; p = 0.000), representing 23.19% and 34.59% respectively. This meta-analysis indicates that the overall effect of nitrate load in drainage is lower for CD by 8.36 kg NO_3 $ha^{-1}year^{-1}$ (33.61%) compared to FD. In the second group is the article by Negm et al. [65], with a similar average value of 9.20 kg NO_3 $ha^{-1}year^{-1}$. In the third group there is also a article by Breve et al. [72] with a mean nitrate load reduction effect (8.42 kg NO_3 $ha^{-1}year^{-1}$) similar to that obtained in the meta-analysis. The total effects for the second and third groups are 1.05 kg NO_3 $ha^{-1}year^{-1}$ higher and 0.09 kg NO_3 $ha^{-1}year^{-1}$ lower, respectively, compared to the overall meta-analysis effect. In addition, a test based on Q statistics showed significant differences between the three test groups (p = 0.000). Also, in 4 (three of the first group and one of the second group) of the studies considered, the results were statistically insignificant for group effects. The resulting total meta-analysis effect was influenced the most by four publications: Youssef et al. [67], Ma et al. [52], Ale et al. [74] and Luo et al. [63], respectively 31.65%, 18.99%, 13.19% and 12.66%, together accounting for 76.49% of the results obtained. Here, the publications of the first

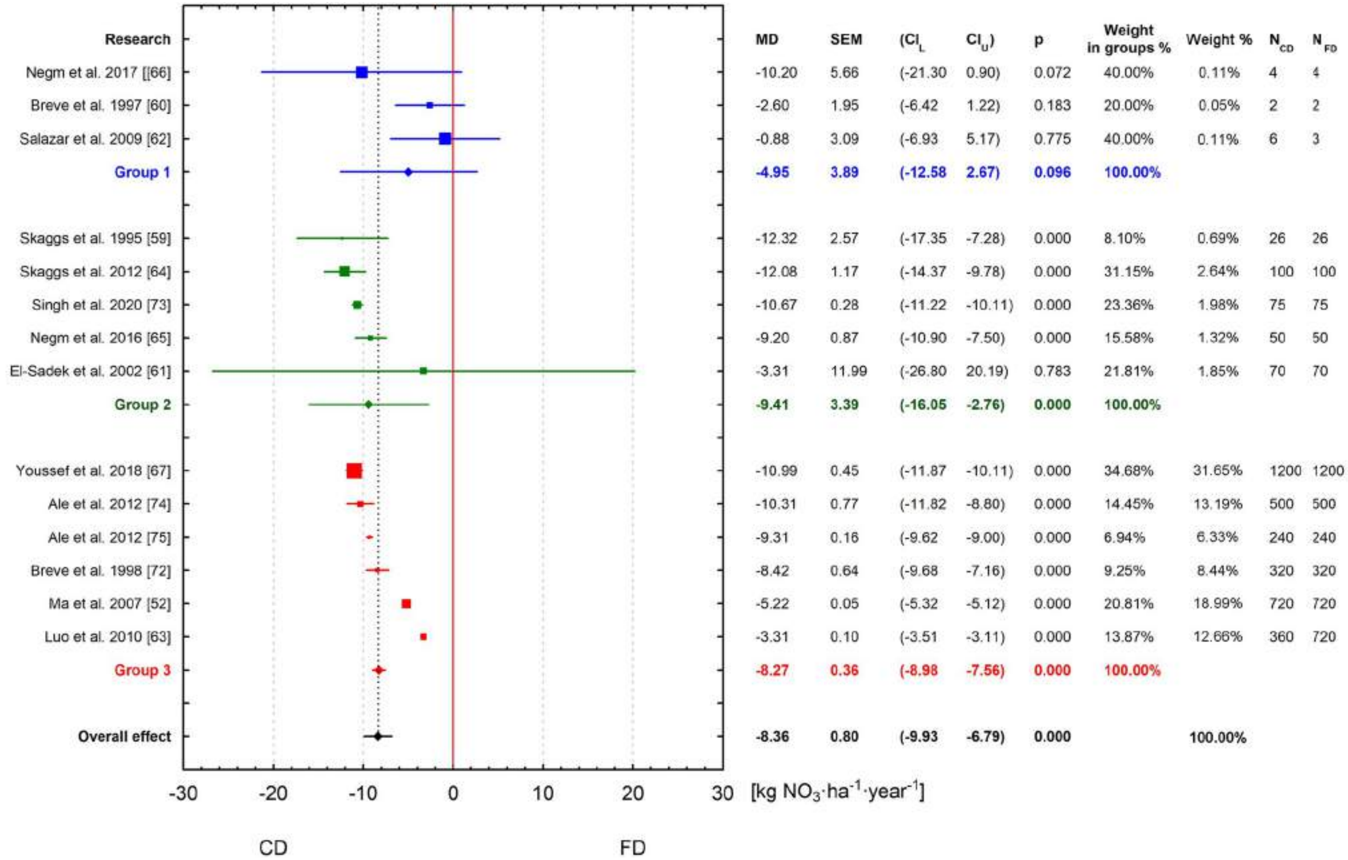

Fig 7. Meta-analysis in groups of nitrate load in drainage outflow by CD versus FD.

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group had the least impact on the total meta-analysis, two publications each of 0.11% and one of 0.05%, together affecting 0.27% of the final result. Two publications, by Salazar et al. [62] and Negm et al. [66], in the first subgroup are the most important, with 40%. In the second subgroup, the largest weight in the subgroup are three publications: Skaggs et al. [64] (31.15%), Singh et al. [71] (23.36%). In the third group, the two publications with the highest weights are those of Youssef et al. [67] and Ma et al. [52], respectively 34.68% and 20.81%.

Publication bias

No signs of publication bias in the studies under consideration for two meta-analyses were shown by the funnel graphs presented in the Begg-Mazumdar test (Fig 8A and 8B). The Egger and Begg tests showed no evidence of publication bias for subsurface drainage outflow reduction and nitrate in drainage outflow by CD versus FD, respectively ($p = 0.336$ for Egger; $p = 1.00$ for Begg's and $p = 0.143$ for Egger; $p = 0.293$ for Begg's). In both graphs, a significant number of studies are at the top of the funnel outside the triangle, but they are close to the edge of the funnel. These are the studies with the smaller standard error and therefore have the strongest influence on the outcome of the analysis. In the funnel plot (Fig 8A), one study is outside the perimeter of the triangle (Pease et al. [69]); the only concern is the selection of this study.

Limitations

The meta-analysis presented above has several limitations. Firstly, there were significant differences in the number of years of outflow and the nitrate reduction modeling for CD and FD

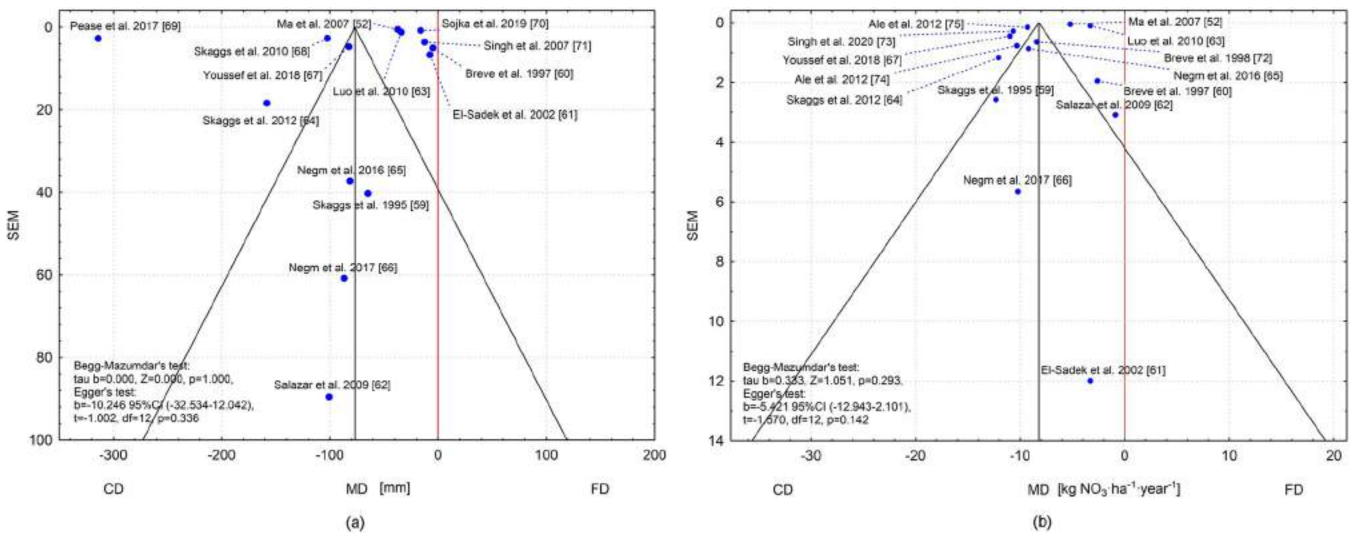

Fig 8. Funnel plot (from Begg-Mazumdar test) for publication bias: (a) subsurface drainage outflow reduction by CD versus FD; (b) nitrate load in drainage outflow by CD versus FD.

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between studies, which may affect average values. Hence, meta-analyses were conducted in groups. Secondly, due to insufficient data and statistical information in some studies, statistical values were calculated on the basis of the values given in the publications for each CD and FD variant. Publications were excluded if they did not contain data on the results of model studies. In the case of missing information, selected meta-analysis publications were not verified and consulted with their authors. Thirdly, this meta-analysis used mean outflow values and nitrate load in outflows in modelled studies. However, the input for each model differed among different studies. In addition, in meta-analysis, sample size and SD are particularly important in combining test results; this issue influenced our study. Furthermore, the effects of publication bias related to meta-analyses cannot be excluded.

Discussion

In their project report from 2002 Abbott et al. [76] stated that CD has the potential to improve water use efficiency, maintain crop yields in periods of water stress, and ensure that land drainage systems work to the maximum benefit of farmers. Many articles supporting this thesis have appeared since this report was prepared.

The current systematic study and quantitative meta-analyses found an average 30.5% reduction of drainage outflow in CD in comparison to FD practice, which averaged 71.26 mm in absolute values. Nevertheless, saving an average of about 71 mm of water by applying CD represents a significant amount of water considering global climate warming that can be used to mitigate adverse climate changes, including droughts. The present results are consistent with those of previous meta-analyses involving field and/or model studies. A meta-analysis presented by Wang et al. [77], including measured rather than simulated data, showed that the combined effect of CD on outflow volume reduction was 19.23%. However, it is worth noting that in this work [77] the combined result was based on both controlled surface drainage (ditches) and subsurface drainage (tile). Considering CD for subsurface drainage only, this effect was significantly higher at about 27.5%. Also according to the review conducted by Ross et al. [78] CD is an effective conservation practice for reducing drainage outflow. The results obtained [78] were significantly higher and CD reduced tile drainage volume by 46% on average. The authors also concluded that the greatest potential for CD to reduce discharge is during the non-growing season and confirmed that the efficiency of CD is especially influenced by drain spacing and management. Also Ale et al. [79] stated that there is reduction of drainage outflow using CD due to its principle of operation, but its effectiveness can vary significantly according to the different course of meteorological conditions, the strategy used, or the different parameters of the drainage network. Based on data from 1915–2006, Ale et al. [79] reported that CD has the potential to reduce annual drain outflow by 114 mm (52%), 94 mm (55%) and 75 mm 55%, respectively for 10 m, 20 m and 30 m drain spacings, relative to FD. Similar conclusions are found in some of the papers used in our meta-analysis [59]. For example, the highest outflow reduction using CD was found in the work of Pease et al. [69] and Salazar et al. [63], where outflow reductions of 95% and 61% were achieved at spacings of 10 and 9 m, respectively. On the other hand, the reductions reported by El-Sadek et al. [61] showed little effectiveness of CD in reducing outflow, averaging about 2.13%. In this case, it may have been due to the wide range of spacing adopted, from 10 to as much as 300 m (Table 1), and the fact that these simulations were carried out for soils with sand texture. The efficiency of drainage outflow reduction depends, among other factors, on climatic conditions, as pointed out by Wang et al. [77]. Based on the data and results in the articles selected for our meta-analysis, it can be concluded that there is a statistically significant negative relationship between total precipitation and reduction efficiency by CD expressed as a % (Fig 9). This suggests that the effectiveness of the CD system is higher for areas with lower precipitation. Such a relationship may be due to the fact that high precipitation amounts force the user to apply the FD practice more frequently to maintain optimal soil moisture.

In meta-analyses conducted in groups the results vary between 22.63% and 33.73% reduction of drainage outflow for CD practice compared to FD. In general, the meta-analysis of the subgroups indicates that as the weights became higher, the heterogeneity of drainage outflow reduction efficiency within the subgroup decreased and statistical significance increased. These weights were mainly determined by the number of study years.

We also found using meta-analyses in the present paper that CD practice is an effective way of reducing nitrogen losses. According to our results, CD significantly reduced the nitrate loading of the drainage outflow. The average reduction in nitrate losses using CD was 8.36 kg $ha^{-1}year^{-1}$ compared to FD, and this was slightly lower than that obtained by Carstensen et al. [80] - 12.00 kg NO_3 $ha^{-1}year^{-1}$ (Fig 3B). However, the heterogeneity of our meta-analysis results was relatively high, and the effectiveness showed a large dispersion around the mean (from to 0.88 kg NO_3 $ha^{-1}year^{-1}$ to 12.32 kg NO_3 $ha^{-1}year^{-1}$), which was not observed in previous studies [80]. This was expected, however, as the effect of CD on the efficiency of nitrate loss reduction depends on many factors, such as cropping system, drainage methods and control drainage management method, climatic and other conditions [43, 64, 77, 78], which varied among the literature items we analyzed. The absolute reduction of nitrate losses was mainly regulated by limiting the amount of water outflow into the drains, which was also emphasized in previous review studies [78]. This is confirmed by our results of the relationship between absolute reduction of drainage outflow and absolute reduction of nitrate expressed by the high value of the determination coefficient (R = 0.92 (Pearson), p = 0.018) (Fig 10A). The reduction in nitrate loading loss using CD solutions expressed in relative values (%) is on average 33.6%, with dispersion ranging from 3% to 53%. This average effect is comparable to that reported by Wang et al. [77] (36%) and lower than that reported by Carstensen et al. [80] (50%). In the case of the relationship between relative reduction of drainage outflow and relative reduction of nitrate losses, the correlation is not statistically significant (R = 0.41 (Pearson), p = 0.274) (Fig 10B), which does not confirm previous findings [80]. As with drainage outflows, in general, a negative correlation between increasing publication weights and heterogeneity within a

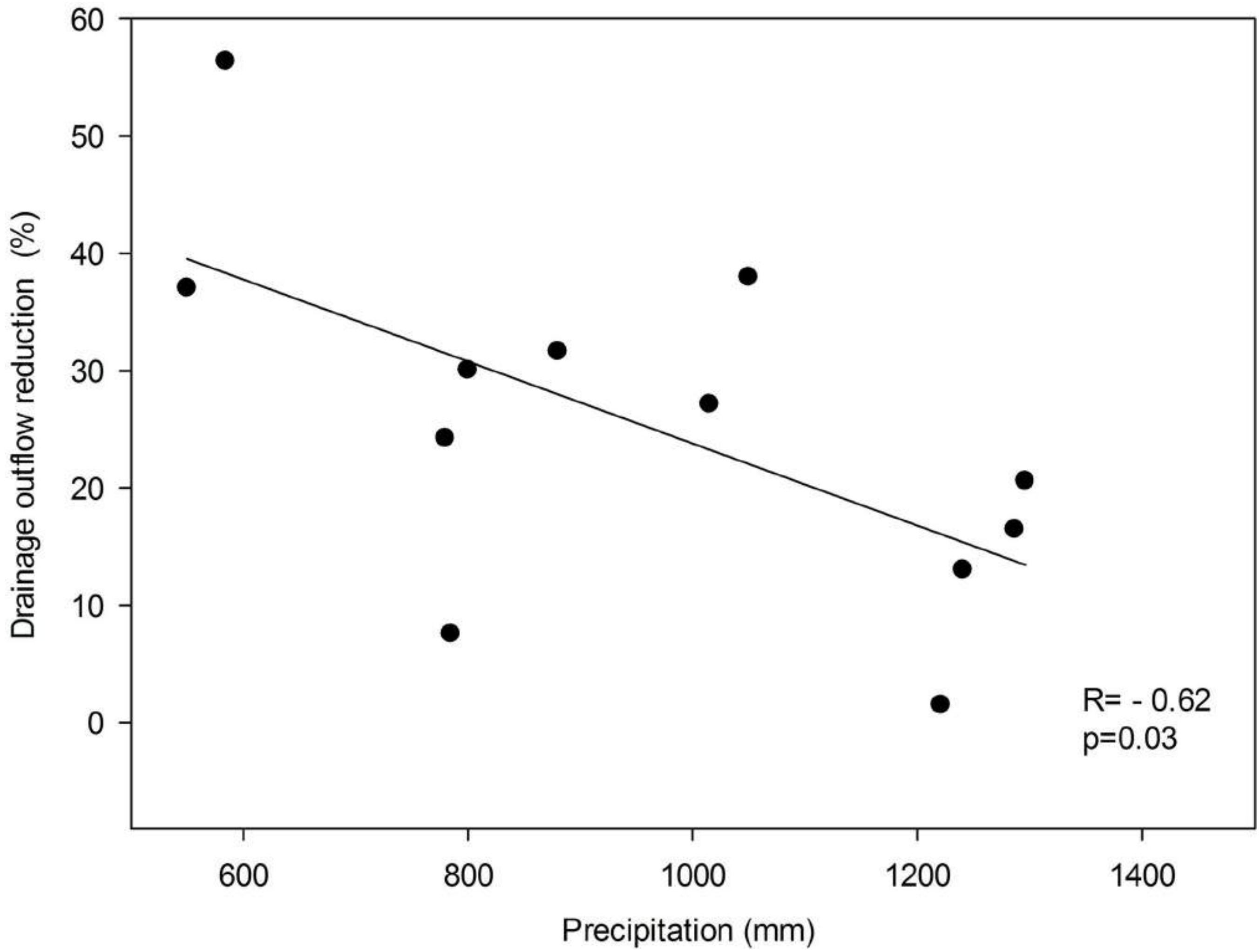

Fig 9. Reduction of drainage water with controlled drainage versus precipitation.

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subgroup and a positive correlation with statistical significance can be found for the meta-analysis of nitrate reduction efficacy subgroups. Since these weights were mainly determined by the number of study years (Table 1), it can be concluded that studies covering a longer period were more statistically significant than those conducted for shorter time intervals. Hence, the overall effect of CD on the reduction of nitrate loading loss in subgroup 1 was statistically insignificant. This first subgroup includes only 3 items of articles with a study period of only 2–3 years. In the other two separated subgroups, the articles were for a much larger number of years; therefore, in both subcluster 2 and subcluster 3, the subgroup effects of CD on reducing nitrate loading loss were statistically significant. For subgroup 2, one literature item [61] had statistically insignificant results for the subgroup effect, which was related to the high variation around the average. The high variable effect of CD on reducing nitrate loading losses in that article was related to drain spacing, which varied widely from 10 to 300 m. This large variation in drain spacing, according to previous findings [78], significantly affects the amount of nitrate leached with drainage water and thus the effectiveness of CD versus FD.

Although the meta-analysis results obtained indicate that CD statistically significantly reduces drainage outflow as well as nitrate loading in drainage water, there is high

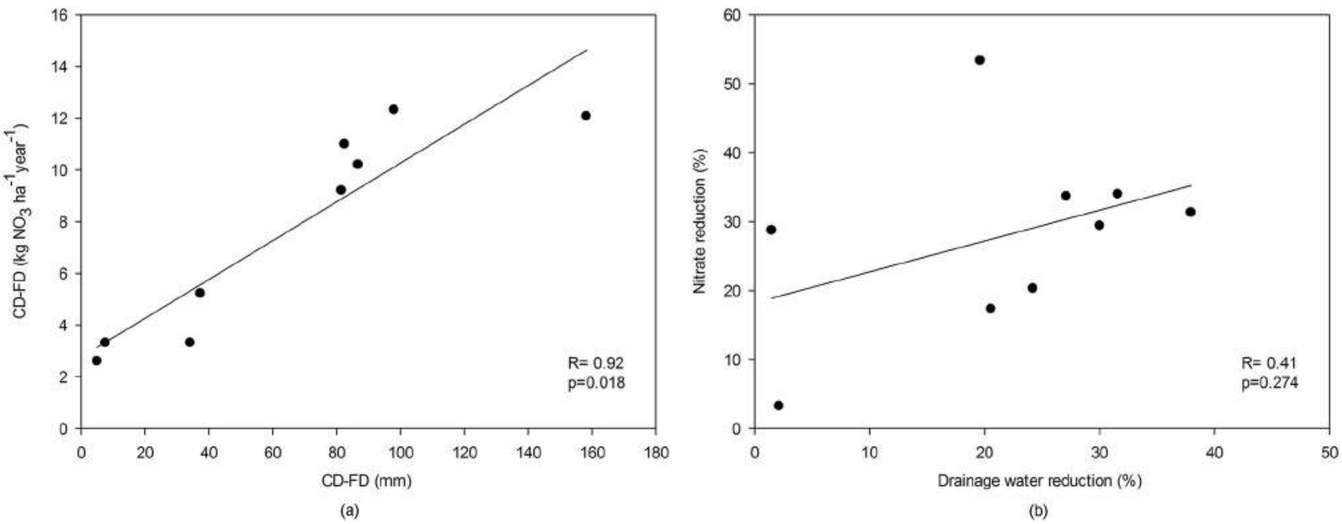

Fig 10. Absolute (a) and relative (b) reduction of nitrate versus absolute and relative reduction of drainage water with controlled drainage.

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heterogeneity of study results within the articles used in our meta-analysis. This is due in part to the varying number of years covered by the studies, as well as factors highlighted in other papers [77, 78, 80]. Hence, we suggest that future studies evaluating the effectiveness of CD compared to FD should be based on measured or model data covering long time periods. While the latter are obtainable from calibrated and validated models, the former are expensive and time-consuming. In addition, modeling studies can be conducted for a wide range of factors affecting CD effectiveness, as well as at different scales [78].

Conclusions

This review study, based on meta-analyses of the scientific literature available until December 2020, indicates that CD is an effective practice for reducing drainage outflows and nitrogen load losses on agricultural land. Overall, CD application reduced the amount of drainage outflow by 30.5%, averaging 71.26 mm in absolute terms. It should be noted, however, that not every application of CD will yield similar quantitative results of water saved. In general, studies covering a longer period of analysis have higher statistical significance for the meta-analysis result than studies conducted for shorter time intervals. The results of this study showed that in agricultural areas, the effect of CD on reducing drainage outflow in relation to FD is more effective where there is less precipitation. For nitrate, the application of CD solutions reduces nitrate load losses with drainage water by an average of 33.61%, which is 8.36 kg NO_3 $ha^{-1}year^{-1}$ in absolute terms. However, the findings of the meta-analysis indicate that the heterogeneity of the results of the effect of CD on reducing nitrate losses with drainage water is very high (from to 0.88 kg NO_3 $ha^{-1}year^{-1}$ to 12.32 kg NO_3 $ha^{-1}year^{-1}$). It decreases with the increasing number of years included in the presented results in individual articles. The reduction of nitrate losses in absolute values was mainly regulated by the reduction of drainage outflows, while a weaker relationship is found between the relative reduction of nitrate losses and the relative reduction of drainage outflows.

Supporting information

S1 Checklist.
(DOC)

S1 Data.
(XLSX)

Author Contributions

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Formal analysis: Barbara Kęsicka.

Funding acquisition: Barbara Kęsicka.

Investigation: Barbara Kęsicka.

Methodology: Barbara Kęsicka, Rafał Stasik, Michał Kozłowski.

Project administration: Barbara Kęsicka.

Supervision: Rafał Stasik, Michał Kozłowski.

Visualization: Barbara Kęsicka, Rafał Stasik.

Writing – original draft: Barbara Kęsicka.

Writing – review & editing: Barbara Kęsicka, Rafał Stasik, Michał Kozłowski.

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8.2. Publikacja P2

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Article

Effectiveness of Controlled Tile Drainage in Reducing Outflow and Nitrogen at the Scale of the Drainage System

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Abstract: The impact of controlled drainage (CD) on the groundwater table (GWT), drainage outflow, surface runoff, and nitrogen reduction at the drainage system scale in the Wielkopolska region was analyzed in this study. Based on field research, mainly by monitoring of GWT changes in 2019–2020, the DRAINMOD model was calibrated and validated. Hydrological soil water balance simulations were carried out with 36 and 9 combinations for CD and free drainage (FD), respectively. The modelling period was March-September for 10 different dry, wet, and normal years from the period of 1961 to 2020. The next step was to use the results of drainage outflow modelling and chemical constituent analyses of drainage water samples to determine NO_3-N concentrations and calculate NO_3-N pollution loads. As a result of the simulations, the importance of the timing of the start of the outflow retention in the adopted model variants was determined, indicating the earliest assumed date of 1 March. The appropriate CD start date as well as the initial GWT has a significant impact on the effectiveness of CD application in reducing the volume of drainage outflow and reducing the amount of NO_3-N entering open water with it. The application of CD under the conditions of the analyzed drainage facility makes it possible to retain up to 22 kg of NO_3-N per hectare.

Keywords: DRAINMOD model; subsurface drainage; groundwater table; drainage water management; nutrients

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1. Introduction

Agriculture is the main diffuse source of both surface water and groundwater pollution, such as nutrients, pesticides or pharmaceuticals, in many European countries [1]. One of the factors affecting excess nutrients in soil and water pollution is the excessive use of fertilizers for plant production derived from mineral and organic fertilizers [2–4]. Nutrients enter the water cycle through erosion, surface runoff, leaching, or inflow from the contaminated discharge of sewage and groundwater into surface waters. The presence of too many nutrients affects water quality and human health [5–10].

Legislative action within the member states of the European Union, the implementation of the Water Framework Directive (WFD) [11], the Nitrates Directive [12], or the Sustainable Use of Pesticides Directive [13] by the Baltic member states is still not effective. These directives specify that the key to achieving good environmental status in marine waters is good water quality in the rivers that flow into the sea. They provide a framework for the protection of inland, transitional, and coastal waters. The objective was to ensure good surface water and groundwater status by 2015 or, in exceptional cases, by 2021 or 2027. Furthermore, the directives require the adoption of measures to ensure that farmers with agricultural land that causes or is likely to cause the nitrate pollution of waterways meet minimum requirements for the use of nitrogen fertilizers. The strategy to improve the condition of the Baltic Sea involves regional cooperation to create a series of recommendations for farmers to reduce nutrient inputs [14–16]. According to the *Second Report of European Waters*, river basin management plans (RBMPs) particularly those involving agriculture, indicate that significant pressures result from pollution from diffuse and point sources. Diffuse water pollution from agriculture (DWPA) was found to affect 22% of the surface water bodies and 28% of the groundwater area, leading to the deterioration of good ecological and chemical status. Point sources are agricultural subsurface drainage systems, and are also known as field, free, or conventional drainage associated with agricultural activities [17].

Non-irrigated agriculture is struggling to cope with more frequent and prolonged extreme events, such as droughts, in various aspects: meteorological, hydrological, agricultural, and socio-economic. The last concerns a water shortfall in relation to the anthropogenic supply and demand in the socio-economic system. Drought is one of the most severe natural hazards, and is also a natural event that occurs in all climates [18,19]. Between 2018 and 2020, Europe experienced a drought of unprecedented intensity that persisted for more than two years. It affected a large part of the continent, with an average surface coverage of 35.6% and an average duration of 12.2 months [20]. Drought in Polish agriculture usually occurred every five years, until recently, when it began to affect significant areas of the country almost every year since 2015 [21]. The economic costs caused by the occurrence of water shortages are losses in agricultural production, so it has become necessary to provide state aid to the affected farmers. In 2015, this amounted to about PLN 500 million; however, in 2018 it was already four times more than this, at just over PLN 2 billion [22].

The agricultural sector is under pressure from a rapidly growing human population affecting the intensification of agricultural production, both plant and animal. Human economic activity and progressive urbanization have a negative impact on water quality. As a result of global climate change, the climate will become drier in some regions, wetter in others, and all areas will be more variable and unpredictable [23,24]. Thus, water-dependent agricultural areas will experience greater water scarcity, while others will become wetter. However, without adaptation to these changes, even regions with relatively smooth projected changes could consequently experience losses in agricultural forage and folder production [25]. The increase in these losses is related to the growing incidence and intensity of agricultural and hydrological droughts in response to rising evapotranspiration and runoff with relatively constant precipitation [26–28]. Hence, agricultural and water policies require accurate information on the impact of climate change on available water resources [29]. A simplified water accounting framework can be fully sufficient to synthesize basin-level information on climate change effects [29] and adaptation measures for the effective planning and management of agricultural water resources [26]. Progressive climate change will require the selection of appropriate crops, as well as the optimization of water management through existing drainage and irrigation systems, among other things [30]. A tile drainage system at field scale is a potential component of agricultural adaptation to climate change. The net effect on the water supply is open to question, but in this case, regions that become drier will experience transition and frictional costs. Referring to data from the year 2000, the variation in the average value of irrigated water, taking into account the variation between crops in different regions, was found to range from 0.09 USD/m^3 in South Asia to 0.42 USD/m^3 in Europe [31].

Poland is one of the member states of the European Union. According to accepted standards, the maximum permissible concentration of nitrate nitrogen in water intended for consumption according to the regulations in force is 50 mg/L of NO_3 (about 11.3 mg/L of NO_3-N), while the recommended value is 25 mg/L of NO_3. These values are recommended by the World Health Organization (WHO) [32,33]. Concentrations of nitrogen compounds in surface waters are important from the point of view of implementing the WFD and achieving good water status. In natural watercourses, average annual concentrations of ammonia nitrogen should not exceed 0.4 mg/L of NH_4-N, nitrate nitrogen should not exceed 2.0 mg/L of NO_3-N, and total nitrogen should not exceed 3.3 mg/L of N [34]. In Poland, the problem of high nutrient pollution is particularly relevant for lowland rivers in intensively farmed areas. Lowland rivers are usually polluted by a large catchment area, and even with a good wastewater treatment system and good agricultural practices, some nutrients reach the waters and pose a threat to their quality [35–38]. According to Janicka et al. [39] the Głuszynka River located in a river and lake system located in a lowland area showed variability in N content, from 0.87 to 9.32 mg/L of N and 0.07–6.95 mg/L of NO_3-N over three years. Fedorczyk et al. [40] reported the average concentration during the growing season of 2019 at the level of 3.4 mg/L for the catchment area of the Glinianka inflow, characterized by a predominant share of arable land (70%) during the recorded drought.

Currently, many countries around the world are increasingly taking action to reduce the loss and recirculation of nutrients to surface waters, slow down the runoff of water, and thus store it [41,42]. The role of subsurface drainage is changing from a single-purpose measure to an important component of an integrated land use drainage and/or irrigation system [43]. The implementation and testing of drainage mitigation measures is becoming a sought-after solution for climate change mitigation and water access in agricultural production. One type of drainage mitigation measures is CD, also known as controlled tile drainage (CTD), which is a part of the drainage water management practices that are increasingly being used in many other countries [41,44,45].

A number of studies on CD have shown that it is very effective in reducing the export of nutrients such as nitrogen and phosphorus in drainage outflows, thereby providing significant environmental benefits [46–49]. In addition, there are studies identifying the positive effects of CD on crop yields and their economic benefits [44,50–53]. However, some studies have found no significant effects of CD [47,54], and in a few cases they have found negative effects, such as a reported decrease in average crop yields [55,56]. Significant differences in the performance of this practice depend on weather conditions such as the amount and timing of rainfall and the management strategy adopted for each year [44]. In addition to experimental field studies, modelling tests are performed for CD application under different spatial, soil and groundwater conditions prior to the installation of equipment. Simulations of field hydrology are carried out for various future climate scenarios of CD application in south-eastern Sweden, central-western Poland, and Ohio, USA [30,57,58].

The aim of this study is to evaluate the impact of CD in comparison to FD practice on the reduction of water outflow from the drainage object in quantitative and qualitative aspects by combining the simulation of hydrological modeling and the results of field measurement. The analyses provide useful information for assessing the impact of drainage management on hydrology and environmental problems related to water and nitrogen at the scale of the drainage system.

2. Materials and Methods

2.1. Study Area Description

The tile-drained agricultural field Ostrowo Szlacheckie (52°21′38.5″ N, 17°36′34.2″ E, elevation 108.38 m above sea level) is located in the central-western part of the Wielkopolska region (Figure 1). The study site is located near a small village, and the agricultural land is used by a private farm that specializes in crop production and cattle breeding. It is located in the central part of the Wielkopolska Lakeland within the Września Plain. Drainage water is discharged directly into a tributary from Gulczewo, which drains into the Rudnik watercourse. The site is hydrographically located in the Warta Water Region. It is in a moderate climate zone, with an annual average precipitation of 521 mm and annual average temperature of 8.8 °C (1951–2020) according to the Poznan meteorological station.

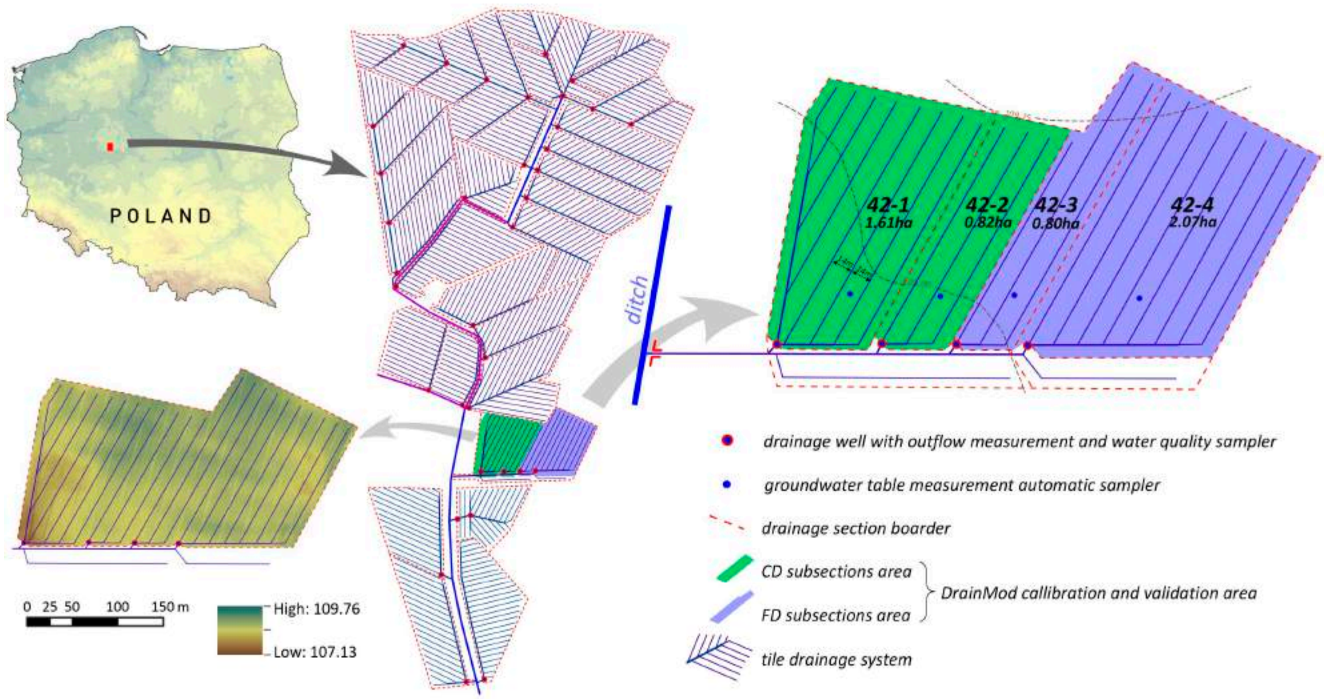


Figure 1. Location of the experiment field, DEM, and overall view of the tile drainage system of the Ostrowo Szlacheckie agricultural land and experimental tile drainage sections 42-1, 42-2, 42-3 and 42-4.

The subsurface tile drainage network was made of PVC pipes using trenchless technology, and it was installed in the 1980s. The standard life expectancy of a network made of plastic perforated pipe used in subsurface drainage is about 50 years. All divisions of this drainage facility have been drained, without problems, for more than 40 years. As can be seen in Figure 1, some of the drainage divisions are characterized by a fairly large area. Water is discharged into the drainage ditch from 22 drainage divisions. The area of drainage sections ranges from 2.53 to 12.54 ha, while for the drainage network system it is about 107 ha. The study included the drainage section No. 42 of 5.30 ha, where the effect of CD on reducing drainage outflows and reducing NO_3-N losses was analyzed. The area is characterized by flat terrain, with slopes of less than 1%. This type of relief, along with homogeneous soil parent materials, causes the soils of the area to be relatively homogeneous. This makes both the depth and spacing of the drains in the entire drainage section essentially the same, at 14 m and 0.9 to 1.0 m b.s.l., respectively. PVC pipes with a diameter of 0.05 m were used. The lateral tiles are connected to the main drain lines (generally from 75 to 150 mm in diameter) that run along the edge of each field. This main drain is connected to an outlet draining into an adjacent drainage ditch. The soils have been classified as Gleyic Luvisols [59], which developed from glacial till. In the soil profile, the surface and subsurface horizon below the argic horizon have a similar sandy loam texture (Table 1). The subsurface "argic" horizon has a higher clay content than the overlying horizons and sandy clay loam texture.

Soil parameters were obtained on the basis of detailed field investigations carried out in experimental drainage section 42. In autumn 2018, after harvesting, eight soil pits were made in order to determine the soil morphological properties according to the FAO [59] and soil sampling guidelines. From each distinguished horizon or subhorizon of pedon, eight samples of undisturbed structure (four to assess the soil water retention curve and four to assess the soil bulk density), and three samples with the disturbed structure were collected (from three walls of the soil pit). The soil texture was analyzed by a combination of the hydrometer and wet-sieve methods, [60] and was then classified following the USDA guidelines [61]. Carbonate content ($CaCO_3$) was determined by applying Scheibler's volumetric method, and the soil organic carbon content was determined by dry combustion in a Multi N/C 3100 apparatus (Analytik Jena). Soil bulk density (BD) was quantified by the core method in a cylindrical sampler of 100 cm^3 [62]. The soil water retention properties were determined using Richards chambers (from 0 to −100 kPa) and the method of using water vapor pressure over a solution of sulfuric acid (from −100 kPa to −1500 kPa) [63,64]. To analyze soil water retention, RETC software was applied to represent the soil water retention curve in the parameters of the van Genuchten equation using the Mualem approach ($m = 1 - 1/n$) [65,66]. The constant hydraulic water gradient method was used to determine the saturated hydraulic conductivity [67]. The basic properties of the soil are listed in Table 1.

Table 1. Average values of soil properties within drainage section No. 42.

Parameter	Unit	Soil Horizon			
		Ap	Bt	Cg or Ck	Ckg
Horizon thickness	cm	36.0	20.75	29.5	60.0
sand content (0.05–2.0 mm)	%	70	64	67	64
silt content (0.002–0.05 mm)	%	21	16	16	19
clay content (<0.002 mm)	%	8	20	18	17
soil bulk density	$g\ cm^{-3}$	1.62	1.77	1.74	1.84
organic carbon content C_{org}	%	1.48	0.61	0.38	0.19
Soil hydraulic parameters					
saturated water content	$cm^3\ cm^{-3}$	0.358	0.315	0.326	0.298
α	cm^{-1}	0.0412	0.0511	0.0620	0.0443
n	-	1.2967	1.1620	1.1910	1.1522
saturated hydraulic conductivity	$cm\ day^{-1}$	43.5	11.8	14.8	7.5
water drainage capacity	$cm^3\ cm^{-3}$	0.127	0.076	0.098	0.062
plant available water	$cm^3\ cm^{-3}$	0.172	0.127	0.134	0.115

Note(s): α and n—parameters of the Van Genuchten equation.

The meteorological data used in the current study were measured at the meteorological station at Sokołowo, 3 km southwest of the Ostrowo Szlacheckie field. As an input date to the DRAINMOD model, a weather file was generated where the measured precipitation (P) and minimal and maximal air temperature (T) were provided at a daily time step from March to September of 2019 and 2020. These data were used to calibrate and validate the model.

GWT was monitored using pressure sensors, called Solinst LTC Leveloggers and Barologger Edge, which were installed in the piezometric wells of section No. 42 to measure GWT on an hourly basis. One well was located on each subsection plot at the midpoint between two drains to increase the accuracy of the monitoring (Figure 1). Measurements were carried out from the beginning of 2019 until the end of August 2021.

Drainage water quality samples were collected manually from February 2019 to June 2020, when the outflow was observed during field work. The samples of 1000 mL polyethylene bottles were collected twice weekly and submitted to the laboratory at the temperature of 4 °C, and were and analyzed in the laboratory within 48 h of their collection. The pH and EC were measured with a pH electrode and conductivity meter, respectively, on unfiltered and unacidified samples. The content of NO_3-N in drainage water was analyzed using the spectrophotometric method in accordance with the standard PN-EN 26777:1999 [68]. Every sample determination was made in duplicate, and the data are presented as averaged values.

2.2. Modeling Procedure

The established research procedure for hydrological modeling of the effect of CD application versus FD on GWT, subsurface outflow, and surface runoff from the drainage facility includes four tasks. The first basic task is the preparation of data from field measurements, laboratory tests, and data analysis of the drainage facility (Figure 2). Based on these, a homogeneous geodatabase of data was created, representing input data consistent with the standard DRAINMOD model. This is a deterministic model that allows one to simulate the hydrology of an artificially subsurface drainage field based on water balance equations. The model can predict drainage outflows, surface runoff, evapotranspiration, lateral seepage, and vertical seepage [44]. The second task involved identifying model parameters, preparing the model, and performing model calibration and validation. The third task was to perform simulations of various scenarios of assumed factors such as the start date of the CD system (none in the case of FD), and initial GWT and meteorological variants, including the amount of precipitation for dry, wet and normal years. The fourth and final task was to subject the obtained results to statistical analysis.

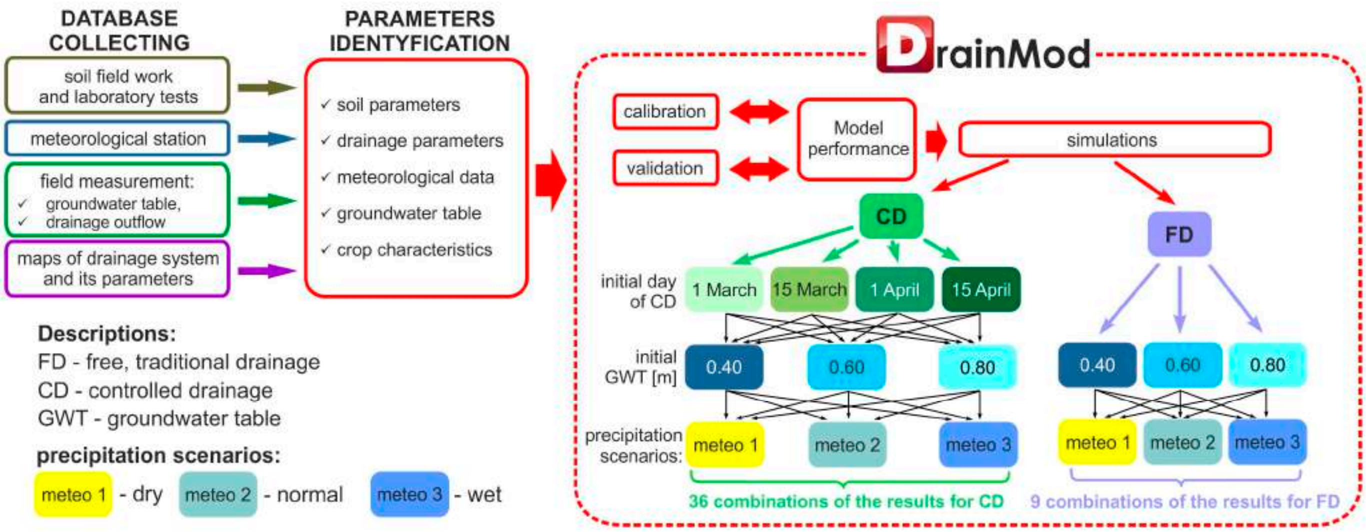


Figure 2. Data collection and modeling procedure.

Thirty-six and nine types of scenario analysis were conducted to study the effects of applied CD and FD practices on the drainage outflow at the scale of the drainage facility. The parameters used in the scenario analysis were as follows: different meteorological conditions including precipitation (dry, wet and normal periods), the initial level of GWT on 1 March, the start date of the simulation, three different variants of 0.40, 0.60 and 0.80 m b.s.l., and CD practice start dates of 1 March, 15 March, 1 April, and 15 April (Figure 2). The initial GWT is required by DRAINMOD for running the hydrology simulation. All analyses were performed for a drain spacing of 14 m.

Simulations were performed for different scenarios of meteorological conditions, including precipitation, for the periods from 1 March to 30 September, on the basis of historical data made available on the website by the Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB) (available online: https://danepubliczne.imgw.pl/ (accessed on 30 September 2021)) for the Poznan meteorological station, for the period of 1961–2020. The annual mean of total precipitation was calculated as 527 mm. For each of the wet, dry and normal year scenarios, 10 years were selected from the multi-year data. The meteorological data used in simulations are presented in Table 2.

Table 2. Basic statistics on annual precipitation, mean annual maximum, and minimum temperature for 10 selected dry, wet, and normal years.

	Dry			Wet			Normal		
	P [mm]	T_{max} [°C]	T_{min} [°C]	P [mm]	T_{max} [°C]	T_{min} [°C]	P [mm]	T_{max} [°C]	T_{min} [°C]
Range	275–403	11.96–15.41	2.88–6.45	632–772	11.83–13.84	3.79–6.14	494–551	10.95–14.35	3.36–6.09
Average	355	13.62	4.71	689	12.99	4.80	519	12.73	4.34
SD	37.31	1.09	0.95	50.15	0.61	0.71	18.26	1.11	0.90

It was assumed that the initial state of GWT was at 0.80 m b.s.l. on the simulation start day (1 March). Thus, the year preceding the simulation was dry, while in the case of the initial state of 0.40 m b.s.l., the year preceding the simulation was wet.

The drainage coefficient was set at 0.011 cm, which was used for the effective radius of drains. The maximum surface storage was set as 0.005 m, and Kirkham's depth for flow to drains was assumed to be 0.5 cm. The drainage coefficient setting was 1.4 cm day^{-1}. The depth to the impermeable layer was set at 4.00 m. We initiated the DRAINMOD soil-related parameters based on the soil properties identified in the previously mentioned field and laboratory studies. In addition, the soil tool package included in DRAINMOD was used to estimate the parameters of the Green-Ampt infiltration model, the drainage volume–water table depth relationship, and the upflux–water table depth relationships.

2.3. Calibration and Validation of the Model

DRAINMOD was calibrated and validated according to the procedure described by Skaggs et al. [69] by comparing the modeled GWT to field measurements. The data collected during 2019 were used for model calibration, while data measured in 2020 were used for model validation. The overall goal of the model calibration was to optimize the model input parameters within reasonable ranges to minimize the difference between the measured and modeled GWT. During the calibration process, the saturated hydraulic conductivity of layer/horizon, the thickness of the restrictive layer, and the hydraulic head at the bottom of the restrictive layer focus were adjusted. The performance of the model was assessed using the following statistical indicators during the calibration and validation procedure: root mean square error (*RMSE*), the coefficient of residual mass (*CRM*), the index of agreement (*d*), and the model efficiency index (*EF*) [70,71]:

$$RMSE = \left(\sum_{i=1}^{n}\left(P_i - O_i\right)^2/n\right)^{1/2} \quad (1)$$

$$CRM = \frac{\left(\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} O_i\right)}{\sum_{i=1}^{n} O_i} \quad (2)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|O_i - O| + |P_i - O|)^2} \quad (3)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(O_i - O)^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O)^2} \quad (4)$$

where n is the total number of observations, O_i is the observed value of the ith observation, P_i the predicted value of the ith observation, and O the mean of the observed values (i = 1 to n). The identification of the model parameters and the procedure for its calibration and validation were carried out as described in detail by Sojka et al. [72].

2.4. Calculations of Drainage Water Quality

Based on the sampled drainage outflows, analyses were performed to determine the characteristic concentrations of nutrient compounds (Table 3) from drainage subdivision 42.

Nitrogen compound loads leached from the catchment were then calculated. These loads were calculated on the basis of the modeled outflows from the catchment using FD and CD practices under different control initiation scenarios in dry, wet and normal years, and with average concentrations of nutrient compounds. Based on the calculated nitrogen unit loads, the amount of nutrient leaching from the entire drainage facility was estimated.

Table 3. The concentration of nutrients from drainage outflows of the analyzed drainage division during the 2019 study period.

Nutrient	**Concentration [mg/L]**			
	Range	**Average**	**SD**	**V**
NO_3-N	14.01–87.98	42.33	17.33	300.35
NO_3	62.03–389.50	187.37	76.72	5886.36

Drainage outflows indicated that the highest proportion of NO_3-N in total nitrogen reached 94%, and that it is the main form of nitrogen. In the case of the values of this nitrogen, speciation ranged from 14.01 to 87.98 mg/L. The content of total nitrogen ranged from 17.48 to 92.02 mg/L.

2.5. Measures of Accuracy and Variable Correlation

Basic statistical parameters were calculated for each drainage and initial GWT variants for dry, wet and normal years. A one-dimensional analysis of variance (ANOVA) and a Tukey's HSD test were used to confirm the existence of uniform (α = 0.05) groups of combinations (applications of FD and CD practices on a drainage site) in terms of varying meteorological conditions for dry, wet and normal years. Calculations were performed using the Statistica 13.3 program (TIBCO Software Inc., Palo Alto, CA, USA).

3. Results

3.1. Quality of the Model

The results of the calibration and validation are shown in Table 4. The *RMSE* values were 0.054 m and 0.069 m, while the *CRM* was 2.1% and 2.9% for calibration and validation, respectively. The *d* and *EF* values for calibration were 0.960 and 0.961, respectively, while for validation the value was 0.947. The results of the calibration and validation are shown in Table 4. The obtained values of *RMSE*, *CRM*, *d* and *EF* for both calibration and validation indicate a very high agreement between the measured and modeled GWT. This indicates that the DRAINMOD model has been well configured, and can be used to simulate the effects of different CD scenarios on the dynamics of the GWT and the drainage outflow of the drained soils.

Table 4. Results of calibration and validation of the DRAINMOD model for GWT prediction.

Year	***RMSE*** **[m]**	***CRM*** **[%]**	***d*** **[−]**	***EF*** **[−]**
		calibration		
2019	0.054	2.1	0.960	0.961
		validation		
2020	0.069	2.9	0.947	0.947

3.2. Groundwater Table Depth

The initial GWT had no significant effect on the variation of the average depth of the GWT for FD practice. The application of the CD practice from 1 March for the distinct groups of dry, wet and normal years results in the highest mean values of GWT in the analyzed period. For this CD practice, three different groups: a, b and c, were distinguished in each year (dry, normal and wet) (Table 5), indicating significant differences in average

GWT between the three variants of the initial GWT. The shallowest water table occurred at an average depth of 117 cm b.s.l. in wet years for the shallowest initial GWT (40 cm). Under normal and wet conditions, the practice variant CD—15 March with 40 cm, 60 cm and 80 cm initial GWT, caused a significant increase in the average GWT compared to FD. The other CD variants (1 April, 15 April) have practically no significant effect on the average GWT values, which are the same as they are for FD. For dry years, this drainage variant CD—15 March, in relation to FD, is effective only for the initial GWT at 40 cm.

Table 5. Average GWT for dry, wet and normal years for drainage variants of the FD and CD of different initial GWT variants.

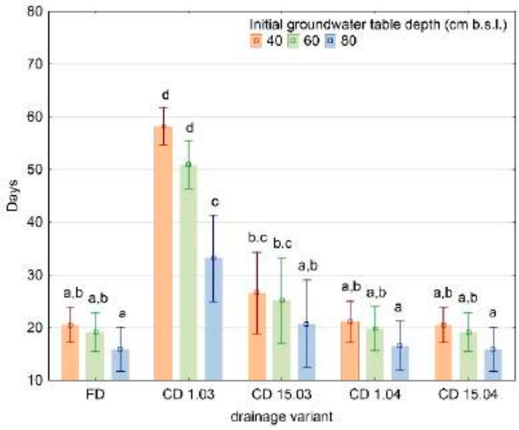
Drainage Variants		Initial GWT Variants (cm b.s.l.)	Average GWT for Years (cm b.s.l.)					
			Dry		Wet		Normal	
FD		40	155.7 ± 0.91	e,f	150.8 ± 0.89	g,h	152.3 ± 0.90	f,g
		60	156.4 ± 0.89	e,f	151.3 ± 0.88	g,h	152.8 ± 0.88	f,g
		80	157.6 ± 0.87	f	152.1 ± 0.86	h	153.6 ± 0.87	g
CD	1.03	40	126.2 ± 1.09	a	117.0 ± 1.07	a	119.3 ± 1.09	a
		60	136.5 ± 1.01	b	127.1 ± 0.98	b	129.7 ± 1.00	b
		80	148.0 ± 0.94	c	138.8 ± 0.90	c	141.6 ± 0.92	c
	15.03	40	151.0 ± 0.94	c,d	142.7 ± 0.88	c,d	146.5 ± 0.91	c,d
		60	152.1 ± 0.92	c,d,e	143.6 ± 0.87	d,e	147.4 ± 0.89	d,e
		80	153.7 ± 0.90	d,e,f	145.2 ± 0.85	d,e,f	148.7 ± 0.88	d,e,f
	1.04	40	155.0 ± 0.90	d,e,f	147.1 ± 0.87	e,f,g	150.1 ± 0.89	d,e,f,g
		60	155.7 ± 0.89	e,f	147.6 ± 0.86	e,f,g	150.6 ± 0.88	d,e,f,g
		80	157.0 ± 0.87	f	148.6 ± 0.84	f,g,h	151.4 ± 0.86	e,f,g
	15.04	40	155.4 ± 0.90	d,e,f	149.0 ± 0.87	f,g,h	150.8 ± 0.89	d,e,f,g
		60	156.1 ± 0.89	e,f	149.5 ± 0.85	g,h	151.3 ± 0.88	e,f,g
		80	157.4 ± 0.87	f	150.4 ± 0.83	g,h	152.0 ± 0.86	f,g

Note(s): Different letters indicate significant differences ($p \leq 0.05$) between variants for each group of years according to a Tukey's test.

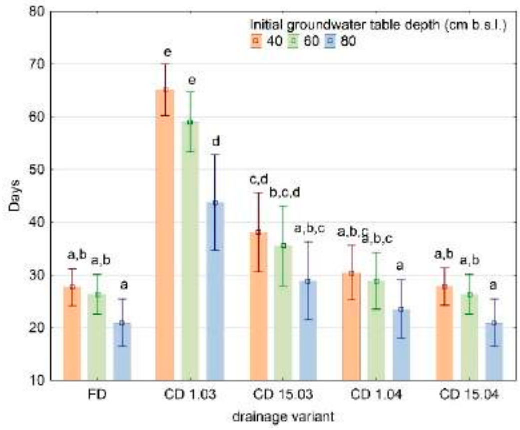
If the CD practice is used for different start options, this allows for a longer period during which the water table is above the drainage network (Figure 3). The most effective variants of this method involve starting to control the outflow on 1 March for different variants of the initial depth of GWT for the three groups of dry, wet and normal years. This increases the number of days that the GWT stays above the level of the drainage network. In this case, in applying CD to a drainage network, it was determined that the residence time of GWT over drains for dry, wet and normal years were 47, 56 and 55 days on average, respectively. For CD variants beginning on 15 March, a slightly lower number of days were obtained in all three year scenarios. The average number of days was 24, 34, and 33 for dry, wet and normal years, respectively. For the scenarios in which the CD was started on 1 April and 15 April, the values obtained indicated that this CD procedure was even less important, and was similar to the FD practice.

3.3. *Subsurface Drainage Outflows*

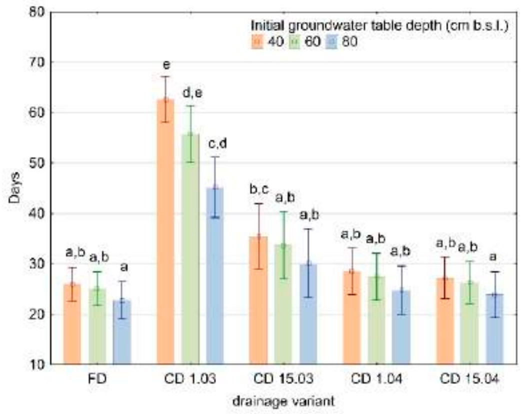
Using the 1 March CD for all three precipitation scenarios, the simulation results indicate three homogeneous groups a, with the smallest value of average outflow (Table 6). For all combinations of CD starting after 1 April and 15 April, the resulting average subsurface drainage outflows are similar to those of FD. Furthermore, no significant differences were found between the combinations for wet and normal years.



(**A**)



(**B**)



(**C**)

Figure 3. Number of days of GWT above the depth of the drainage network under different variants of controlled drainage for dry (**A**), wet (**B**) and normal (**C**) years (bar charts show the average values and standard deviation, different letters indicate significant differences ($p \leq 0.05$) between variants of drainage according to a Tukey's test).

Table 6. Average subsurface drainage outflows for the dry, wet and normal for drainage variants of FD and CD of different initial GWT variants.

Drainage Variants		**Initial GWT (cm b.s.l.)**	**Average Subsurface Drainage Outflows (mm)**					
			Dry		**Wet**		**Normal**	
FD		40	48.0 ± 17.0	f	52.4 ± 13.7	i	52.2 ± 11.8	g
		60	31.8 ± 16.6	d,e	35.8 ± 13.5	f,g	35.7 ± 11.6	e
		80	15.0 ± 15.8	b,c	18.4 ± 12.9	c,d	18.1 ± 11.3	c
CD	1.03	40	0.9 ± 0.2	a	1.1 ± 0.3	a	1.0 ± 0.2	a
		60	0.7 ± 0.3	a	0.7 ± 0.2	a	0.7 ± 0.3	a
		80	0.4 ± 0.3	a	0.4 ± 0.2	a	0.4 ± 0.2	a
	15.03	40	40.7 ± 5.7	e,f	41.9 ± 6.9	g,h	43.6 ± 3.0	f
		60	25.0 ± 5.5	c,d	26.2 ± 6.8	d,e	27.7 ± 3.0	d
		80	8.9 ± 4.9	a,b	10.0 ± 6.1	b,c	11.1 ± 2.8	b
	1.04	40	47.2 ± 16.1	f	49.1 ± 12.3	h,i	49.3 ± 8.3	f,g
		60	31.1 ± 15.7	d,e	32.6 ± 12	e,f	32.9 ± 8.1	d,e
		80	14.5 ± 14.9	b,c	15.4 ± 11.3	c	15.4 ± 7.8	b,c
	15.04	40	48.0 ± 17.0	f	52.3 ± 13.7	i	50.3 ± 8.8	g
		60	31.8 ± 16.6	d,e	35.8 ± 13.4	f,g	33.8 ± 8.7	d,e
		80	15.0 ± 15.8	b,c	18.3 ± 12.8	c,d	16.2 ± 8.3	b,c

Note(s): Different letters indicate significant differences ($p \leq 0.05$) between variants for each group of years according to a Tukey's test.

The use of CD makes it possible to reduce the number of days with drainage outflow in comparison to FD (Figure 4), thereby extending the period during which GWT is retained on the site. The most effective option is to start retaining outflow on 1 March for all variants. In each group of years, a homogeneous group a is indicated for each variant, indicating the absence of days with recorded drainage outflow on that date. When starting the withholding of the drainage outflow on 15 March for the dry and wet years of the initial GWT variants, similar results were obtained. When the CD practice started on 1 April and 15 April, there was a similar increase in the number of days for each GWT variant. In addition, identical homogeneous groups were observed for the indicated initial GWT variants in these years.

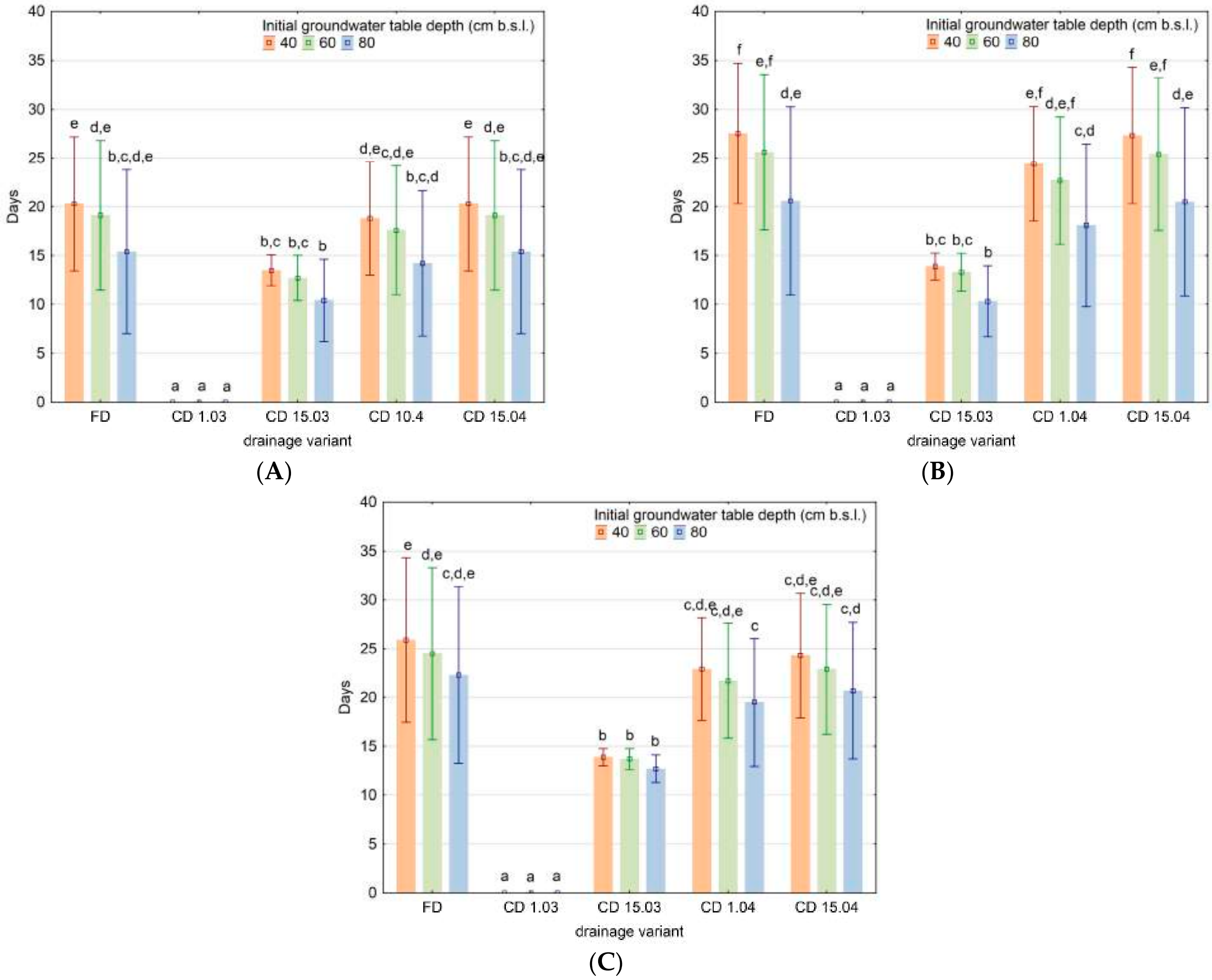


Figure 4. Number of days with drainage outflow for different drainage variants under dry (**A**), wet (**B**), and normal (**C**) years (bar charts show the average values and standard deviation, different letters indicate significant differences ($p \leq 0.05$) between variants of drainage according to a Tukey's test).

For the adopted precipitation scenarios, the greatest effects of reducing drainage outflows by CD were obtained in the cases where the outflow blockage began on 1 March (Figure 5). Accordingly, for the cases starting from the setting of all the initial GWT variants, outflows can be reduced by up to 100%. If the date for blocking outflows is moved to 15 March, the reduction is significantly lower, with an average of 13%, 27% and 19%, for dry, wet and normal years, respectively. The start of CD practice on 1 April showed outflow reductions of 1.3–3.0%, 7.8–16.6%, and 2.3–6.5% for dry, wet and normal years, respectively. No effect was observed when the blockage of outflows started on 15 April.

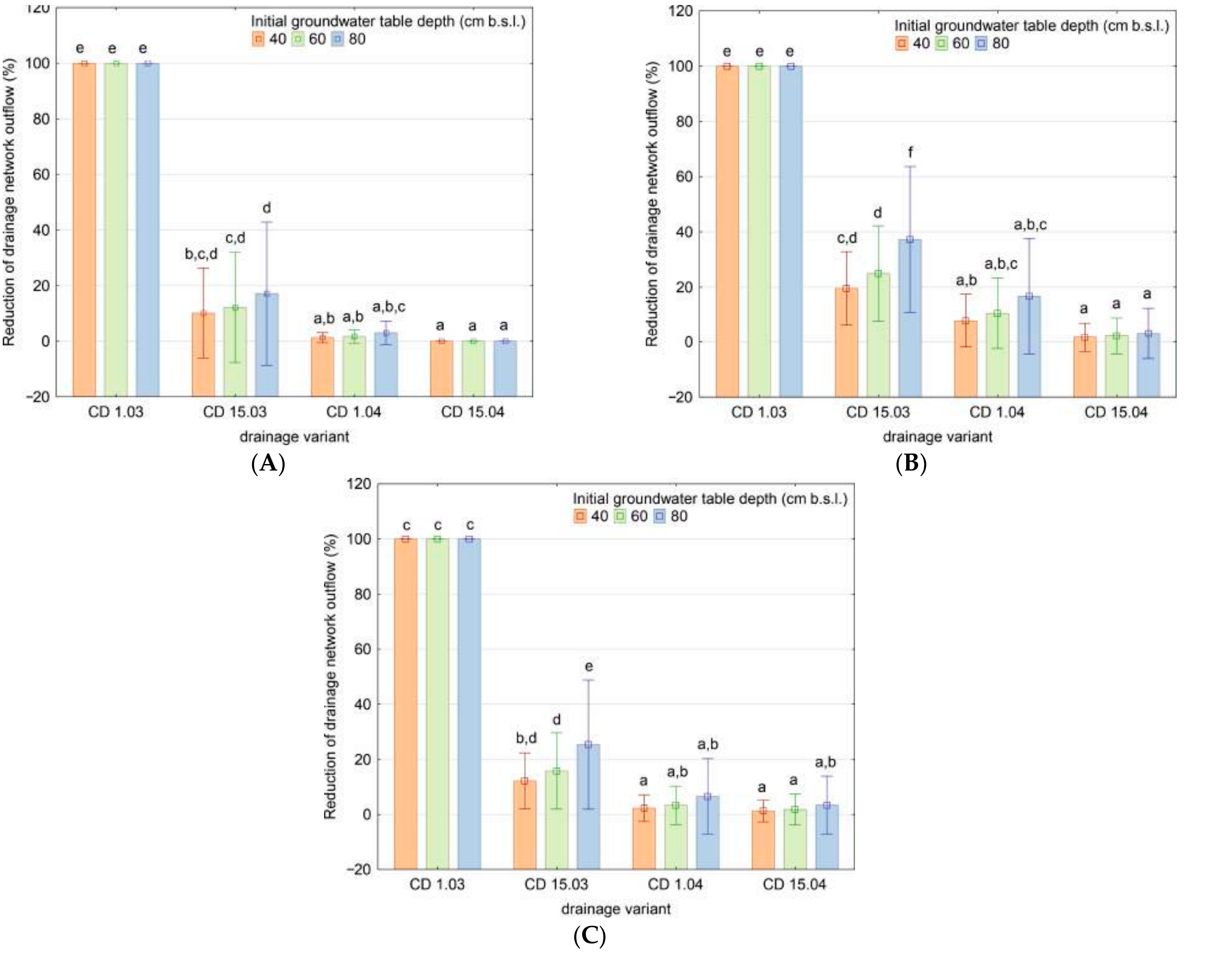


Figure 5. Reduction of drainage outflow for different drainage variants under dry (**A**), wet (**B**), and normal (**C**) years (bar charts show the average values and standard deviation, different letters indicate significant differences ($p \leq 0.05$) between variants of drainage according to a Tukey's test).

3.4. Surface Runoff

Surface runoff is particularly important in terms of erosion and the loss of nitrogen compounds. The simulation results show that surface runoff is small (Figure 6). The calculations showed that for the flat terrain analyzed, CD practices do not have a statistically significant effect on differences in surface runoff in either dry, wet, or normal years. Slight differences, although not statistically significant, may relate to the practice of early CD on 1 March in the case of a shallow GWT (40 and 60 cm b.s.l.). This means that under these conditions, the runoff process may lead to higher losses of nitrogen compared to other CD variants.

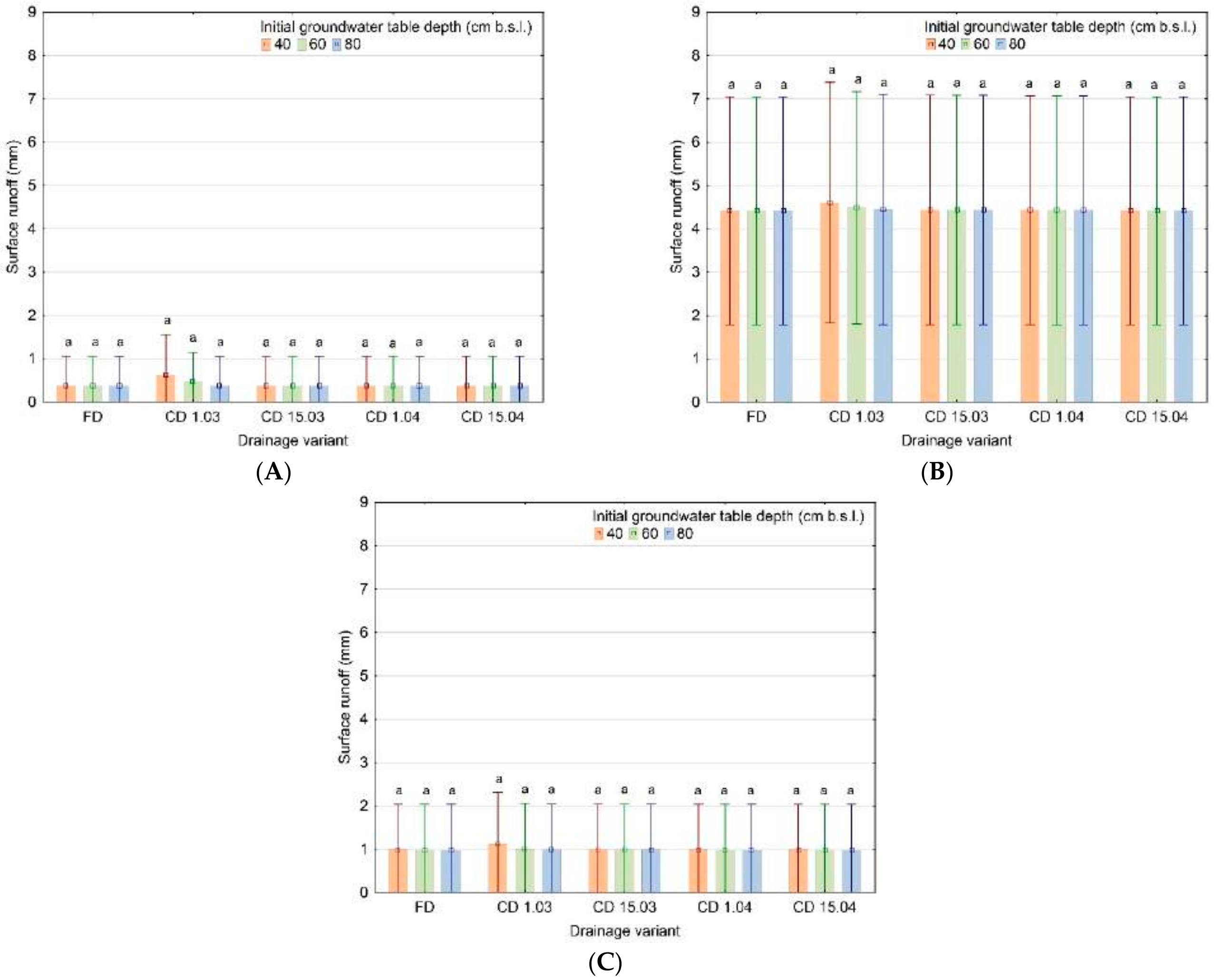


Figure 6. Surface runoff for different drainage variants under dry (**A**), wet (**B**), and normal (**C**) years (bar charts show the average values and standard deviation, different letters indicate significant differences ($p \leq 0.05$) between variants of drainage according to a Tukey's test).

3.5. Nitrate Outflow Reduction

The analysis of NO_3-N loads indicated a significant reduction in discharge with drainage outflow from the analyzed subdivisions when CD was applied on 1 March in all precipitation scenarios (Table 7). This is indicated by the classification of this date into a homogeneous group a with a range of 0.15 to 0.45 kg ha^{-1}. The CD practice, which began on 1 March, allows for a reduction in load leaching from 6.22 to 21.71 kg ha^{-1} compared to FD. Starting the CD on 15 March in the variant of the initial GWT at 80 cm indicates lowering the NO_3-N load of 2.58–3.56 kg ha^{-1}. The other two dates for the start of the CD indicate similar results to the FD practice. If the initial depth of withholding the outflow is considered, the largest average values of loads are for 40 cm b.s.l., while the smallest are for 80 cm b.s.l. Similar differences in NO_3-N load between wet and dry years were obtained for FD and CD variants that started on 1 April at 1.39–1.84 kg ha^{-1}.

As expected, a 100% reduction in NO_3-N loads for CD practice started on 1 March (Table 8). For the two-week later start of CD practice, the reduction was significantly smaller. This is considerably higher than the later dates when CD was started. For dry years, there was no reduction in load leaching for the 1 April CD.

Table 7. Average NO_3-N (kg ha^{-1}) loads for drainage subdivisions 42-2 and 42-3 for dry, wet, and normal years.

Drainage Variants		Initial GWT (cm b.s.l.)	Load NO_3-N (kg ha^{-1})					
			Dry		Wet		Normal	
FD		40	20.32	f	22.16	i	22.11	g
		60	13.46	d,e	15.16	f,g	15.11	e
		80	6.37	b,c	7.79	c,d	7.67	c
CD	1.03	40	0.00	a	0.00	a	0.00	a
		60	0.00	a	0.00	a	0.00	a
		80	0.00	a	0.00	a	0.00	a
	15.03	40	17.25	e,f	17.75	g,h	18.46	f
		60	10.60	c,d	11.08	d,e	11.75	d
		80	3.79	a,b	4.23	b,c	4.68	b
	1.04	40	20.00	f	20.77	h,i	20.88	f,g
		60	13.16	d,e	13.80	e,f	13.90	d,e
		80	6.12	b,c	6.52	c	6.51	b,c
	15.04	40	20.32	f	22.14	i	21.28	g
		60	13.46	d,e	15.13	f,g	14.29	d,e
		80	6.37	b,c	7.76	c,d	6.86	b,c

Note(s): Different letters indicate significant differences ($p \leq 0.05$) between variants for each group of years according to a Tukey's test.

Table 8. NO_3-N reduction of drainage network for different drainage variants in dry, wet, and normal years.

Drainage Variants		Initial GWT (cm b.s.l.)	Reduction of NO_3-N (%)					
			Dry		Wet		Normal	
CD	1.03	40	100	e	100	e	100	c
		60	100	e	100	e	100	c
		80	100	e	100	e	100	c
	15.03	40	10.11	b,c,d,	19.48	c,d	12.20	b,d
		60	12.20	c,d	24.90	d	15.77	d
		80	17.13	d	37.21	f	25.37	e
	1.04	40	1.30	a,b	7.77	a,b	2.29	a
		60	1.70	a,b	10.44	a,b,c	3.31	a,b
		80	3.04	a,b,c	16.63	a,b,c	6.54	a,b
	15.04	40	0.00	a	1.74	a	1.24	a
		60	0.00	a	2.22	a	1.78	a
		80	0.00	a	3.13	a	3.35	a,b

Note(s): Different letters indicate significant differences ($p \leq 0.05$) between variants for each group of years according to a Tukey's test.

The total annual NO_3-N loads discharged from the whole drainage system are a fairly accurate representation of the loads reported for discharge from the drainage network. The lowest loads were observed for the CD practice that started on 1 March for each precipitation scenario (Table 9). The later dates for the start of CD give similar results for the removal of loads from the drainage system to the FD practice. The highest values were observed for the FD practice for wet years in all GWT variants.

Table 9. Total NO_3-N removed from the surface of the entire drainage facility for different drainage variants in dry, wet, and normal years.

Drainage Variants		Initial GWT (cm b.s.l.)	NO_3-N (kg)		
			Dry	Wet	Normal
FD		40	2166.87	2363.40	2357.79
		60	1435.21	1616.44	1611.56
		80	679.19	830.53	818.15
CD	1.03	40	42.60	48.20	45.01
		60	30.07	31.57	32.02
		80	16.24	17.99	18.32
	15.03	40	1839.40	1893.56	1969.08
		60	1130.39	1181.28	1252.61
		80	403.77	450.69	499.15
	1.04	40	2132.58	2214.98	2226.90
		60	1403.88	1471.62	1482.89
		80	652.60	695.27	694.30
	15.04	40	2166.87	2360.73	2269.10
		60	1435.21	1613.80	1523.53
		80	679.19	828.02	731.78

4. Discussion

The results obtained in this study indicate that it is possible to effectively increase the groundwater table, reduce subsurface outflow from the drainage network, and reduce NO_3-N losses through CD practices. Thus, CD solutions provide opportunities to insert more water and NO_3-N into the soil-water-atmosphere-plant system. For an area with slopes not exceeding 1% where the soils have been developed from sandy loam, significant CD efficiency occurs when outflows are blocked during 1–15 March. Blocking drainage outflows at a later date does not lead to a significant increase in GWT or a reduction in water and nitrate losses compared to FD.

Reducing water outflows with CD practice starting at 1–15 March reduces outflows by 37–100%, 25–100%, and 17–100%, in wet, normal and dry years, respectively. The ranges of reduction in drainage outflows obtained in this study for the recommended time of CD implementation (1–15 March) correspond to those reported by other authors [44,73–80]. Skaggs et al. [73,75,76] achieved an average reduction in outflow of 6–42% with annual precipitation ranging from 907 to 1760 mm. Similar values were reported by Williams et al. [78], Negm et al. [79], and Youssef et al. [80]. In contrast, El-Sadek et al. [81] obtained the smallest reduction in outflow (0.8–4.1%) in sandy soil, with an average annual rainfall of 868 mm. Variations in the results of the effect of CD on drainage outflow reduction may be attributable to different climatic conditions, soil properties, and technical parameters of the drainage network [78]. Our results showed that for years differing in terms of annual precipitation, the reduction in drainage outflow varies even when starting the CD practice on the same dates and with the same initial GWT. The maximum amount of water that can be saved by the CD practice starting on 1 March with an initial GWT of 40 cm is 48–52 mm. Ale et al. [76] obtained an average annual reduction in drainage outflow of 51 mm for the Hoagland Ditch watershed. The later decision (1–15 April) to use CD under the analyzed conditions does not reduce the duration (days) of drainage outflows compared to FD.

In addition to regulating drainage outflows through CD practices, it is also important to control GWT, especially from the point of view of the water needs of plants. Furthermore, changes in GWT are a valid parameter in assessing the effectiveness of CD. The obtained results showed the highest average GWT for the CD practice starting on 1 March for all water depth variants (40 cm, 60 cm and 80 cm). The 1 March start date of CD practice results in an increase in the average GWT for the March to September period. The highest values of GWT increase were observed for the 40 cm initial variant. A similar maximum rise of the GWT (36 cm) during the growing season was observed by Ale et al. [74]. As drainage outflows become blocked, the time of the GWT above the drains increases. However, for variants with an initial GWT in the 40–80 cm range, the number of days of this extension in relation to FD is similar for both dry (17–37 days) and wet (23–37 days) years. In relation to FD, the application of CD on 15 March also results in a significant increase in average GWT, and thus an increase in the number of days with the GWT above the drains. However, these effects are significantly smaller than for those resulting from the blocking of the drainage outflow on 1 March.

Along with the blockage of drainage outflows and rising GWT, the potential danger of generating surface runoff increases [82,83]. In analyzed flat terrain, the results of the statistical analyses showed that CD practices have no significant effect on the increase in surface runoff. Slightly higher values of surface runoff, although not statistically significant, may relate to the CD practice starting on 1 March when the initial GWT is shallow (40 and 60 cm).

CD practices can have a significant impact on the reduction of nutrient losses. This mainly concerns NO_3-N, which can be easily leached from the soil to the drainage water. The results indicated that CD practice application use on 1 March can even reduce NO_3-N losses completely (100%). The losses at later dates were similar to those obtained in FD practice. Liu et al. [84] reported that the total reduction in NO_3 losses (91% and 99%) with CD were closely related to reduced drain outflow rates (88% and 98%). Tolonio and Borin [85,86] found that CD reduced the outflow by 69% and 81% compared to FD, respectively. They also reported that CD reduced annual nitrogen losses by 92% (from 29 to 2 kg NO_3-N ha^{-1}) compared to FD, where losses were 46 kg NO_3-N ha^{-1}. Wang et al. [87] concluded that the implementation of CD reduced the loss of NO_3-N by 20.53% and reduced the amount of drained water by 19.23%. Some studies have demonstrated that CD has been effective in reducing nitrate-nitrogen loss due to a reduction in drainage outflow [88]. In the case of 15 March, the NO_3-N loss reduction was about 10–17%, 12–25%, and 19–37% for dry, normal, and wet years, respectively. A similar reduction of 27–32% was reported by Ma et al. [89]. Salazar et al. [90] observed higher NO_3-N losses for an annual rainfall of 722 mm (7.9–10.1 kg ha^{-1}) than for an annual rainfall of 578 mm (0.1–0.4 kg ha^{-1}) from a plot with CD practice. Poole et al. [91] found that CD reduced NO_3-N export by 30%, with an average annual reduction of 6.3 kg ha^{-1} per $year^{-1}$. According to our results, the entire drainage facilities of the investigated area of CD can reduce the total amount of NO_3-N from 830–2363 kg to 18–48 kg compared to FD in wet years. This confirms the most significant benefit of CD, as the reduction in drainage outflows reduces the NO_3-N load. This will significantly reduce the supply of nitrates of agricultural origin to water bodies, thereby improving the ecological status of surface waters by significantly reducing the degree of eutrophication [15,16].

The relevance of the research is important in relation to the current, ageing infrastructure and the potential design of new subsurface drainage infrastructure for agricultural fields in Poland. Climate change is influencing adaptation measures in agriculture in terms of water management. Adaptive drainage water management strategies, e.g., CD, for drained agricultural landscapes are increasingly being implemented to identify opportunities for water storage or diversion. Answers are being sought as to how drainage systems should be designed and used in the future. This is influenced by the changing approach to drainage, from an emphasis on rapid one-way removal of all water, to investigating how water can be controlled within agricultural fields for production and water quality purposes.

5. Conclusions

The above presented results and their analyses allow us to draw the following conclusions:

1. The control of water outflow from the drained field in the Wielkopolska region using CD practice proved to be the best strategy when starting from 1 to 15 March. The

simulation showed the best performance by reducing the drainage outflow and thus reducing nutrient losses. An increase in the groundwater table during CD practice does not affect the surface runoff in relation to FD.

2. Starting the CD practice on 1 to 15 March can reduce drainage outflow by 37–100%, 25–100%, and 17–100% in wet, normal, and dry years, respectively. The amount of drainage outflow that will result from the later decision (1 to 15 April) to run the CD is statistically similar to those drainage outflows for the FD.
3. In dry years, starting CD practices in the period of 1 to 15 March makes it possible to significantly raise the groundwater table and to extend its duration above the level of drains, by an average of 33–58 days when compared to FD. In wet and normal years, the extension is similar, at about 55 days. An increase of groundwater in the analyzed flat arable area does not affect the surface runoff.
4. The most effective reduction of NO_3-N losses was observed for CD practice from 1 to 15 March. This reduction is approximately twice as high in wet years in comparison to dry years. The later start of CD practices has no significant effect on NO_3-N reduction compared to FD.
5. The application of CD under the conditions of the analyzed drainage facility makes it possible to significantly reduce the discharge of NO_3-N. With this technique, it is possible to retain up to 22 kg of NO_3-N per hectare.

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8.3. Publikacja P3

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Article

Controlled Drainage Effectiveness in Reducing Nutrient Outflow in Light of Climate Changes

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Abstract: This modeling study focused on the hydrological and water quality effects of controlled drainage (CD) when operated using a subsurface drainage system in an agricultural field in the Wielkopolska region. The DRAINMOD hydrologic model was well calibrated and validated in an experimental field. This model was used in the performance of CD and free drainage (FD) combinations (108 and 27, respectively) in a near-future climate change scenario. The objective was to understand the potential of CD on the groundwater table (GWT), drainage outflow, surface runoff, and nitrogen and phosphorus reduction under projected climate conditions in Poland during the 21st century with shared socioeconomic pathway SSP370. The results indicated that the earliest start of CD practice is the most effective in increasing GWT. Compared to current climatic conditions, when applying CD on 1 March in the near future, with an initial GWT of 60 and 80 cm b.s.l. in wet years, drainage outflows will increase by 33% and 80% for the GFDL model, by 30% and 40% for the MPI model, and by 17% and 23% for the UKESM model. Comparing the surface runoff values obtained to current climate conditions, the MPI, GFDL, and UKESM models predict a significant increase in surface runoff in the near future, which is due to the predicted increase in precipitation. The annual NO_3–N reduction was by 22, 19, and 15 kg per hectare for wet, normal, and dry years, respectively, in the near future. Among the climate scenarios, the UKESM model predicted higher NO_3–N and PO_4 leaching values compared to the MPI and GFDL models.

Keywords: drainage water management; subsurface drainage; field hydrology; agriculture; water quality; water balance; modeling

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1. Introduction

One of the fundamental components of protecting surface water in most European Union countries is the conducting of a realistic assessment of the quantity of nitrogen compounds and other nutrients that are released from agricultural catchments [1–3]. This evaluation is critical because it determines the fate of the water, particularly when it is at a high risk of eutrophication, such as in the case of the Baltic Sea [4]. Its watershed covers 14 countries, including Poland, which is situated on the coastline and encompasses approximately 18% of the area. Nutrient loads originating from Poland are carried by the Vistula and Oder rivers, as well as the nine rivers of the Przymorze, contributing an estimated 30% of the total nitrogen load introduced into the basin [5]. This is mainly due to the fact that 59.8% of Poland's land is used for agriculture, with 72.4% of it being arable land where crops are accompanied by the intensive application of fertilizers, particularly mineral or chemical nitrogen fertilizers [6]. Considering the additional intensive livestock breeding in Poland, it is assumed that agriculture is the primary economic sector responsible for introducing the largest amount of nutrients into surface waters [7].

The intensification of land use and changes in land and water management in agriculturally used areas necessitates the exploration of new adaptive solutions to realize the potential of artificial agricultural subsurface drainage systems [8–11]. Presently, depending on the region, they are primarily used for two purposes: to enhance and facilitate the management of soil water associated with salinity and waterlogging and to unilaterally remove excess water, thereby improving soil aeration and field access [12]. As such, tile drainage has been identified as the primary pathway for delivering nutrients and other pollutants to surface waters, which is a significant factor given that an estimated 34% of total agricultural land in northwest Europe is artificially drained. Consequently, reducing the leaching of pollutants from agricultural land into drainage systems could assist in mitigating pollution from agriculture [13]. Therefore, reducing losses from the primary sources of nutrients and their mobilization by enhancing nutrient use efficiency is necessary, and the field scale appears to be an appropriate level to assess this progress [14].

One solution to this issue is CD, which is utilized to decrease the amount of drainage outflow at the scale of the drainage facility, thus reducing the quantity of N and P loads discharged. Annual reported reductions in discharge have ranged from 7% to 68%, while reductions in NO_3–N loadings have ranged from −8% to 63% in the USA. However, these studies analyzed the effects of CD on P loading and have reported mixed results, with changes in total P (TP) loading ranging from no effect to 77% reductions [15–17]. Helmers et al. [18] demonstrated that CD led to reductions in drainage volume by 28%, 33%, and 52% under wet, normal, and dry precipitation scenarios, respectively. Additionally, Wang et al. [19] showed a meta-analysis that revealed that CD reduced subsurface drainage volume by approximately 30% for dryland crops. Studies conducted in European countries indicated varying degrees of reduction in drainage volume, ranging from 37% in Denmark to 95% in Sweden; moreover, reductions in nitrate-N were observed, from 36% in Denmark to 100% in Italy. Regarding TP reduction, the percentage of reduction varied, with values ranging from 43% to a range of 56–95% [20–22]. Taking into account the expected effects of climate change and local physical, geographical, and climatic conditions, environmental and technical solutions are being developed using drainage mitigation measures [23]. These solutions should be able to accommodate future climate changes and agricultural land use, with the aim of achieving crop production goals while minimizing environmental impacts. By implementing effective adaptation measures together with appropriate agrotechnical measures, integrated solutions for water management in drained areas can be developed [24].

Drainage systems are typically designed with a lifespan of more than thirty years, making them a significant long-term investment. Consequently, it is crucial to conduct research on the potential impact of projected climate change on the performance of agricultural and drainage water management systems [25,26]. Simulation modeling of hydrological changes is the prevailing approach employed to evaluate how climate change could affect the efficacy of future adaptation strategies [27]. While numerous field campaigns have been conducted to investigate the effects of CD, challenges arise when attempting to test diverse scenarios involving meteorological conditions and hydrological linkages [17,28]. Models offer a valuable means of assessing the effectiveness of various water management strategies in both present and future climate scenarios [29–31]. Abdelbaki [32] indicated that the implementation of CD had a minimal effect on subsurface drainage, resulting in a reduction of less than 15% in the outflows during both historic and future periods. Similarly, CD demonstrated consistent changes in nitrogen losses in the drainage outflows, with a slight reduction projected for the future. The CD led to an average decrease of 4.42 kg N ha^{-1} yr^{-1}, equivalent to 17.25% during the historic period, and a further reduction of 7.25 kg N ha^{-1} yr^{-1}, corresponding to 25.75%, during the future period. Pease et al. [33] noticed that CD exhibited enhanced efficacy during summer, with reductions in subsurface drainage outflow increasing to 42.7% for the Representative Concentration Pathway (RCP) 4.5 emission scenario and 81.8% for RCP 8.5 under late-century climate conditions. Such evidence of the advantages of implementing CD practice in current climate conditions will continue to be applicable under projected future climate scenarios. Sojka et al. [30], who conducted simulations on the effects of CD, using RCP 4.5, observed a decreased duration of the GWT above the drainage depth in future projections. Consequently, this led to a reduced impact of CD on GWT and drainage outflow. According to Salla et al. [31], when CD is applied in future climate scenarios, it is projected to significantly impact the GWT, leading to an average increase of 1–4 cm compared to historical data. It achieves this by reducing annual drain discharge by approximately 41.3 to 46.2 mm and 22.4 to 26.1 mm in RCP 8.5, as well as 41.3 to 43.2 mm and 21.0 to 24.8 mm in RCP 2.6, respectively. These results highlight the relevance and viability of CD as an effective method for mitigating drainage outflow, particularly in milder winter conditions in the future.

The purpose of this study was to determine the effect of CD on the GWT, drainage outflow, and N and P losses from agricultural fields in Greater Poland. Simulations have been carried out, assuming changes in temperature and precipitation in line with the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) simulations, in particular the third round of ISIMIP3b, as part of the international Coupled Model Intercomparison Project 6 (CMIP6). It focuses on regional scale changes in agriculture for three models (Geophysical Fluid Dynamics Laboratory (GFDL), Max Planck Institute Earth Model (MPI), and UK Earth System Model (UKESM)) for predicting the impact of future climate changes. Our study uses the SSP370 scenario with an additional radiative forcing of 7 W m^{-2} by the year 2100. This scenario is in the upper-middle part of the full range of scenarios and has been newly introduced, closing the gap between RCP6.0 and RCP8.5. To know the seasonal effects of CD, it is necessary to study long-term simulations with future climate predictions and assess the change in the near future. Through modeling the time period 2021–2050, this study considers varying parameters, including different weather conditions, initial GWT conditions, and the implementation of CD solutions with specific drain blocking dates. The objective is to analyze the outcomes and implications of employing CD in order to mitigate the impacts of climate change on the amount of drainage water and crop cultivation. Furthermore, the study aims to investigate the feasibility of achieving favorable surface water quality by reducing nutrient loading from agricultural land. The results obtained from this research will provide valuable insights into the potential contributions and effectiveness of CD in addressing the challenges posed by climate change in relation to crop production and water quality management.

2. Materials and Methods

2.1. Study Area Description

The study site is a drainage field of arable land located in Ostrowo Szlacheckie (Figure 1) in the central-western part of Greater Poland, Poland (N 52°21′38.5″ and E 17°36′34.2″). In late 2018, modifications were made to drainage section number 42, which is divided into four subsections. Two of these subsections were equipped with CD, while the remaining two were maintained as FD. The study area is flat (average slope of less than 1.0%), and the soils within it, based on field and laboratory studies, were classified as Gleyic Luvisols [34]. The spacing of drains was 14 m, while the tile depth was 0.9–1.0 m. The basic soil properties of the analyzed study area are shown in Table 1.

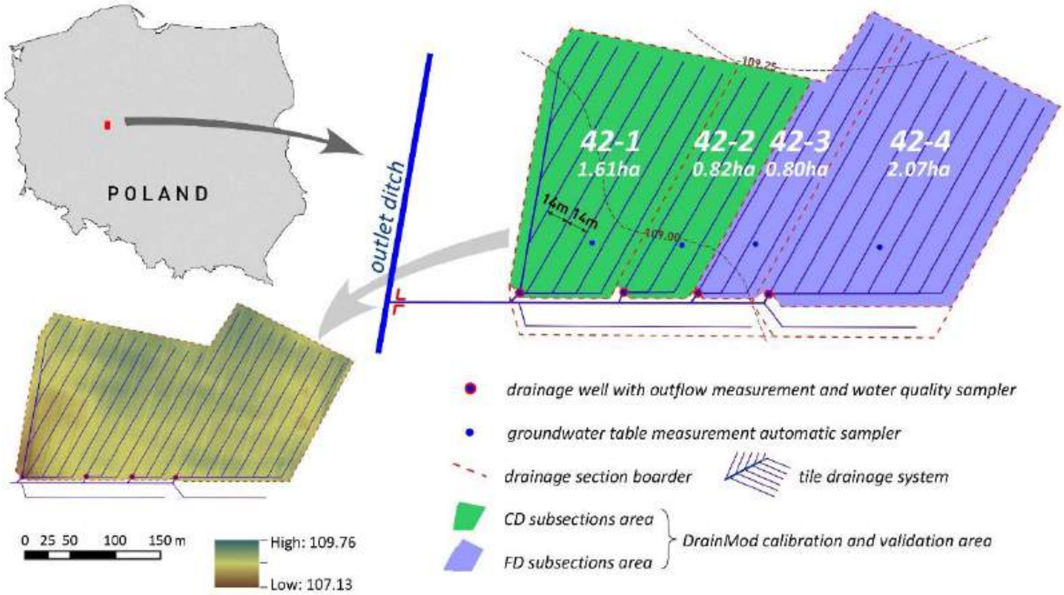

Figure 1. The drainage experimental field in Ostrowo Szlacheckie.

Table 1. Input model parameters for soil layers of drainage section No. 42.

Horizon	Thickness (cm)	Sand/Silt/Clay (%)	Bulk Density (g cm^{-3})	Organic Carbon Content (g kg^{-1})	Saturated Water Content (cm^3 cm^{-3})
Ap	36	70/21/9	1.62	14.8	0.358
Bt	21	64/16/20	1.77	6.1	0.315
Cg or Ck	29	67/16/17	1.74	3.8	0.326
Ckg	60	64/19/17	1.84	1.9	0.298
Horizon	**α (cm^{-1}) ***	**n (-) ***	**Saturated Hydraulic Conductivity (cm day^{-1})**	**Water Drainage Capacity (cm^3 cm^{-3})**	**Field Capacity (cm^3 cm^{-3})**
Ap	0.0412	1.2967	43.5	0.127	0.231
Bt	0.0511	1.1620	11.8	0.076	0.239
Cg or Ck	0.0620	1.1910	14.8	0.098	0.228
Ckg	0.0443	1.1522	7.5	0.062	0.236

* α and n—parameters of Van Genuchten equation.

During the CD experiment in 2019–2020, GWT was recorded hourly and separately from the CD area and the FD area using Solinst LTC Leveloggers and Barologger Edge. Also, the depths of the GWT were observed manually (approximately once a week) using the study plot. Hourly meteorological data were gathered from the experiment meteorological station at Sokołowo, next to the Ostrowo Szlacheckie field. Daily data were used for the measured precipitation (P) and minimum and maximum air temperature (T). These data from March–September 2019–2020 were used to calibrate and validate the model.

A comprehensive description of the study area, the field measurement equipment installed, and details of the fieldwork and laboratory analyses carried out can be found in the publication by Kęsicka et al. [34].

The main forms of biogenic compounds were determined in water samples from drainage outflows. Table 2 outlines the standard methods employed to determine various parameters, including nitrite nitrogen and orthophosphate (V).

Table 2. Nutrient concentrations determined in drainage water samples from the facility.

Analyses	Methodology	ISO Standard Method	Concentration [mg/L]	
			Average	SD
Nitrate nitrogen (NO_3–N)	spectrophotometric method	PN-EN 26777:1999 [35]	42.33	17.33
Orthophosphate (PO_4)	spectrophotometric method	PN-EN 1189:2000 [36]	1.66	1.19

2.2. Climate Data

The daily maximum and minimum air temperature, as well as precipitation data, were obtained from the ISIMIP Repository for this study. A selection of three global climate models (GCMs) (Table 3) was made for a one-time horizon to the near future (2021–2050). The future climate projections were based on the SSP370 scenario for the Poznań meteorological station (45 km from the field) [37]. This particular scenario, known as "regional rivalry", assumes an expected radiative forcing level of 7 W m^{-2} by 2100, with a focus on regional dynamics, while global issues are given less priority [38]. The data used in this study were bias-corrected at a resolution of 0.5° grid cell [37]. The average values of these parameters were obtained from data from grid cells around Poznań and then compared to the simulated values of the historical period (1971–2000) and the observed values from the Institute of Meteorology and Water Management–National Research Institute (IMGW-PIB).

Table 3. Climate change projection models included in this study.

Model Name	Institute
GFDL-ESM4	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, Princeton, United States of America
UKESM1-0-LL	Met Office Hadley Centre, Exeter, United Kingdom
MPI-ESM1-2-HR	Max Planck Institute for Meteorology, Hamburg, Germany

Figure 2 shows the temporal development of variables, describing the climate conditions, especially historical precipitation during the years 1971–2000, which were used to choose models for the simulations. The average annual precipitation recorded for the Poznań meteorological station from the analyzed multi-year period is 507 mm. For the selected GFDL, MPI, and UKESM models, it is 582, 599, and 583 mm, respectively.

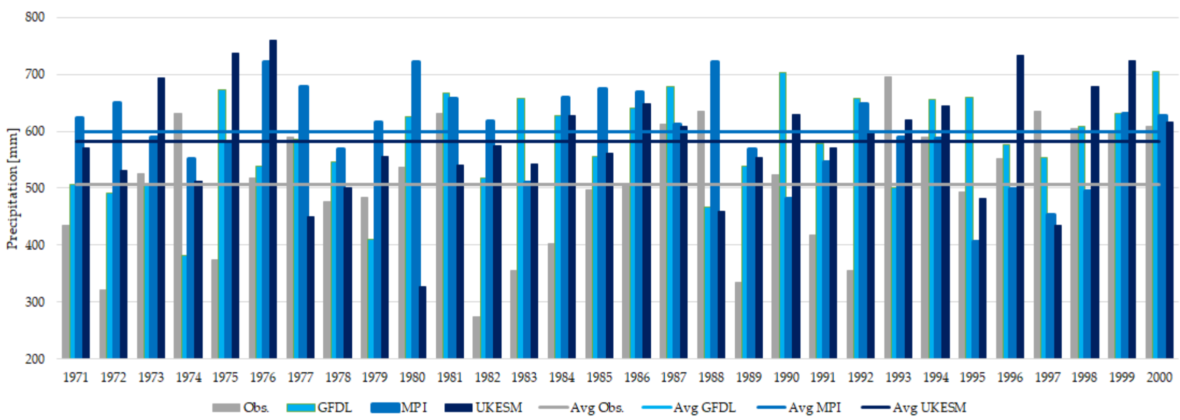

Figure 2. Annual mean precipitation for the Poznań meteorological station and historical projected data are presented for GFDl, MPI, and UKESM climate change models for 1971–2000.

Figure 3 shows the temporal variation of precipitation in the near future of 2021–2050 for the SSP370 scenario for Poznań. The annual mean value of precipitation in the used future scenario is 651, 626, and 620 mm for the GFDL, MPI, and UKESM models, respectively.

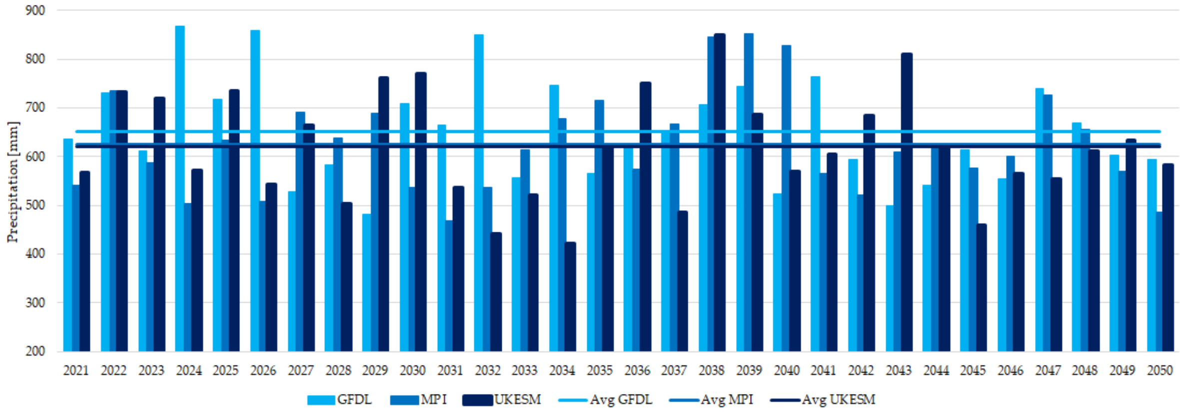

Figure 3. Annual mean precipitation projected data are presented for GFDl, MPI, and UKESM climate change models for 2021–2050.

2.3. DRAINMOD

The DRAINMOD model is an open-source, deterministic, hydrological model that allows for the prediction of changes in the water balance of agricultural land under different drainage systems and practice scenarios. The model uses five groups of input data such as drainage system characteristics, soil properties data, crop information, weather data, and management data (irrigation schedule, fertilizer application, rates, and GWT control strategies). These input data parameters are used by the DRAINMOD model to simulate hydrological processes, water movement, and nutrient transport in agricultural subsurface drainage systems. The model provides output data, such as drainage outflow, water table depth, crop water use, and nutrient losses, which can be used to evaluate the performance and impact of the drainage system and inform management decisions. The model uses soil hydraulic parameters according to Mualem [39] and Van Genuchten [40]. Drainage outflow in most cases is calculated from the Hooghoudt equation; however, when the water table reaches the surface and the land surface is further flooded, the outflow rate is calculated using the Kirkham equation [41]. Surface runoff is calculated when the user-defined soil storage capacity is the difference between rainfall and infiltration rate, using the Green–Ampt equation [42]. This model uses the Thornthwaite method to calculate daily evapotranspiration from maximum and minimum temperatures [43].

2.4. Model Setup

The simulations were performed for different scenarios for the periods from 1 March to 30 September. A total of 108 and 27 modeling scenarios (Figure 4) were performed for the assumed input parameters for CD and FD, respectively, to test the effectiveness of the practices used. The following modeling input parameters were established: different meteorological conditions (wet, normal, and dry years due to precipitation), initial GWT on 1 March, simulation start date, three different variants of 0.40, 0.60, and 0.80 m below surface level (b.s.l.), and CD practice start dates of 1 March, 15 March, 1 April, and 15 April. All analyses were conducted for a drain spacing of 14 m. The drainage coefficient and maximum surface storage were set at 0.011 cm and 0.005 m, respectively. Kirkham's depth for the flow into the drains was set at 0.5 cm, while the drainage coefficient was set at 1.4 cm day^{-1}. The depth of the impervious layer was 4.00 m. We originated DRAINMOD soil-related parameters based on soil properties (Table 1). In addition, the soil tool package provided in DRAINMOD was used to determine the parameters of the Green–Ampt infiltration model, the relationship between drainage volume and upflux, and water table depth. The prepared DRAINMOD model, in accordance with the procedure indicated by Skaggs et al. [44], was calibrated and validated using field measurement data from 2019 and 2020, respectively. Multiple rounds of adjusting input parameters were carried out to achieve an acceptable level of agreement and minimize differences between observed and modeled GWT data. Model performance analysis was performed using statistical indicators during the calibration and validation procedure, such as the root mean square error (*RMSE*), residual weight ratio (*CRM*), consistency index (*d*), and model efficiency factor (*EF*) [45,46]:

$$RMSE = \left(\sum_{i=1}^{n} (P_i - O_i)^2 / n \right)^{1/2} \tag{1}$$

$$CRM = \frac{\left(\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} O_i\right)}{\sum_{i=1}^{n} O_i} \tag{2}$$

$$d = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (|O_i - O| + |P_i - O|)^2} \tag{3}$$

$$EF = 1 - \frac{\sum_{i=1}^{n} (O_i - O)^2 - \sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - O)^2} \tag{4}$$

where n is the total number of observations, O_i is the observed value of the ith observation, P_i is the predicted value of the ith observation, and O is the mean of the observed values (i = 1 to n).

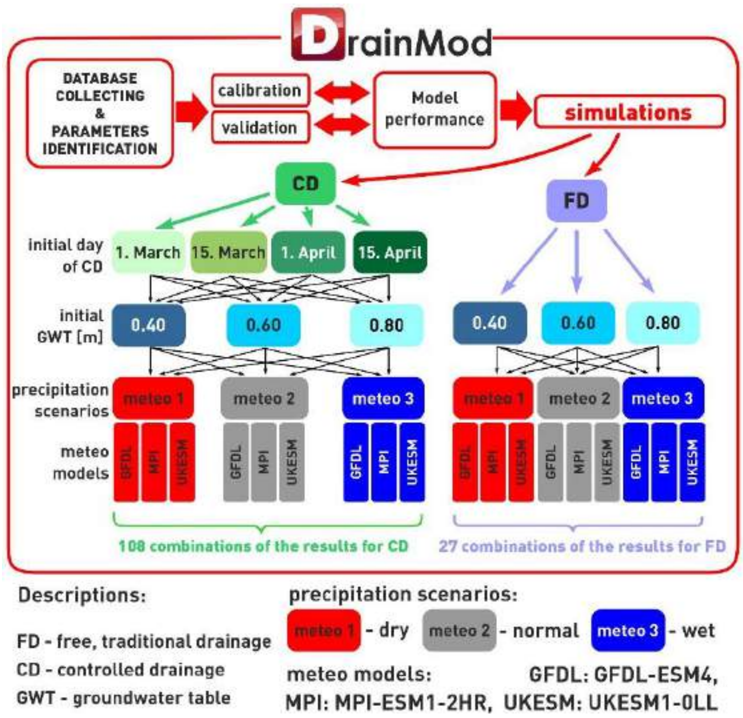

Figure 4. Modeling procedure in DRAINMOD.

2.5. Processing Output Data

DRAINMOD modeled daily values for the output variables. The results were examined by dividing the years 2021–2050 into three groups of years (wet, normal, and dry) and into three consecutive variants using climate change models (GFDL, MPI, and UKESM). These variants were used to combine data (GWT, subsurface drainage outflows, surface runoff, and loads of nutrients) to indicate the climatic and hydrologic conditions of each combination of the results for CD. The statistical significance between each drainage and initial GWT variant for dry, wet, and normal years was analyzed using ANOVA and Tukey's HSD significance test with $\alpha = 0.05$. The Statistica 13.3 program (TIBCO Software Inc., Palo Alto, CA, USA) was used for calculations.

3. Results

3.1. Quality of Model and Data

For the configured DRAINMOD model, the obtained calibration and validation process RMSE values were 0.054 m and 0.069 m, while, for CRM, they were 2.1% and 2.9%, respectively. The d and EF values for calibration were 0.960 and 0.961; for validation, the value was 0.947. The indicated model quality characteristics obtained for both calibration and validation indicate very high agreement between measured and modeled GWT. The prepared DRAINMOD model can be used to simulate the impact of different CD scenarios for the projected climate change on the dynamics of the GWT and drainage outflow of a drainage facility.

Using daily historically measured and predicted precipitation data ranked from lowest to highest, a data fit analysis was performed for the selected models. Figure 5 shows the basic quality statistics for selected GFDL, MPI, and UKESM models of SD < 1, RMSE < 0.5, and r > 0.95.

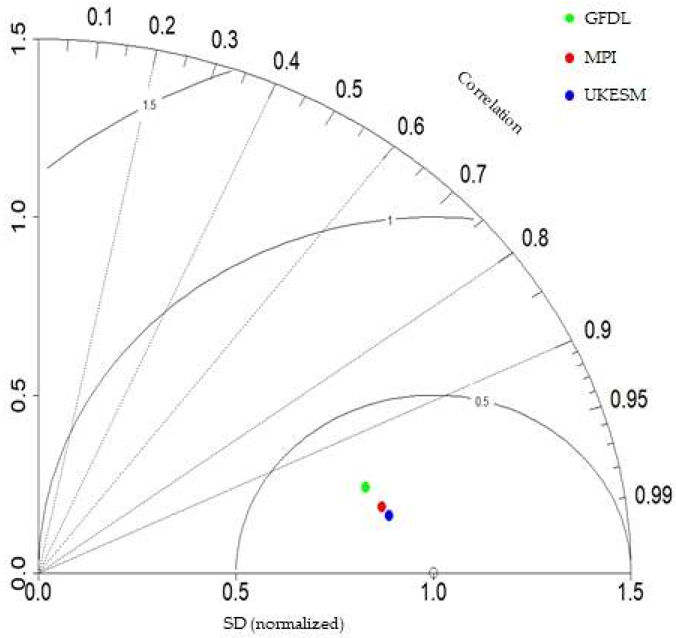

Figure 5. Taylor graph showing a statistical comparison between observations of GFDL, MPI, and UKESM model estimates of global future climate projections of precipitation for Poznań.

3.2. Effect of CD on GWT

Changes in GWT due to projected climate change were more evident in the results obtained for the GFDL and UKESM models (Table 4). In their case, the start of CD in the 1 March deadline indicated the shallowest GWT in the analyzed period. Based on the GFDL model data, GWT can increase by 27–41, 12–33, and 11–31 cm on average, as well as, for the UKESM model, by 14–34, 17–33, and 8–29 cm in wet, normal, and dry years, respectively. After this date, in the March–April period, the GWT decreased to the depth indicated for FD modeling. In CD simulations based on MPI model data, the practice start dates of 1 March and 15 March resulted in the GWT being maintained at similar depths in the adopted modeling variants. Based on the MPI model data for the start of the CD dates of 1 March and 15 March, similar results were obtained for the GWT, which can, on average, increase by 23–39, 19–36, and 16–35 cm in wet, normal, and dry years, respectively. Later start dates for withholding outflow resulted in a flattening of the water table to the FD practice.

Table 4. Average GWT for wet, normal, and dry years for FD and CD practice of different initial GWT variants for GFDL, MPI, and UKESM models.

Drainage Variants		Initial GWT (cm b.s.l.)	Average GWT (cm b.s.l.)					
			Wet		Normal		Dry	
GFDL								
FD		40	153.20 ± 5.50	h	153.99 ± 3.58	e	157.77 ± 4.04	g
		60	153.59 ± 5.53	h	154.54 ± 3.73	e	158.46 ± 4.38	g
		80	154.11 ± 5.56	h	155.53 ± 4.16	e	159.68 ± 5.22	g
CD	1.03	40	112.27 ± 8.08	a	121.36 ± 8.44	a	126.86 ± 10.46	a, b
		60	117.40 ± 9.10	a, b, c, d	131.51 ± 10.10	a, b, c	137.03 ± 11.98	b, c, d
		80	127.34 ± 11.00	b, c, d, e	143.41 ± 10.94	c, d, e	149.08 ± 12.36	d, e, f, g
	15.03	40	140.55 ± 11.17	e, f, g, h	147.54 ± 8.41	d, e	152.82 ± 8.35	e, f, g
		60	141.34 ± 11.14	e, f, g, h	148.53 ± 8.47	d, e	153.82 ± 8.49	e, f, g
		80	142.49 ± 10.99	f, g, h	150.15 ± 8.71	d, e	155.53 ± 8.98	g
	1.04	40	150.54 ± 7.35	g, h	151.92 ± 5.17	e	157.11 ± 3.98	g
		60	150.95 ± 7.37	g, h	152.50 ± 5.29	e	157.81 ± 4.33	g
		80	151.48 ± 7.37	g, h	153.54 ± 5.71	e	159.04 ± 5.19	g
	15.04	40	151.13 ± 6.47	g, h	153.15 ± 3.25	e	157.20 ± 3.92	g
		60	151.52 ± 6.50	g, h	153.70 ± 3.39	e	157.90 ± 4.26	g
		80	152.04 ± 6.53	g, h	154.70 ± 3.87	e	159.11 ± 5.11	g
MPI								
FD		40	151.90 ± 4.25	g, h	155.15 ± 3.66	e	155.72 ± 3.92	g
		60	152.29 ± 4.30	g, h	155.63 ± 3.80	e	156.27 ± 4.03	g
		80	152.90 ± 4.50	h	156.30 ± 4.11	e	157.14 ± 4.31	g
CD	1.03	40	113.22 ± 10.54	a, b	118.89 ± 7.14	a	120.91 ± 10.32	a
		60	119.65 ± 13.48	a, b, c, d	126.91 ± 9.83	a, b	130.47 ± 13.06	a, b, c
		80	130.26 ± 16.36	d, e, f	137.46 ± 11.91	b, c, d	141.45 ± 15.86	c, d, e
	15.03	40	115.75 ± 8.66	a, b, c	120.04 ± 6.53	a	121.93 ± 8.81	a
		60	121.05 ± 12.34	a, b, c, d	127.31 ± 9.27	a, b	131.01 ± 12.06	a, b, c
		80	130.03 ± 15.16	c, d, e, f	137.60 ± 11.70	b, c, d	141.96 ± 14.73	c, d, e, f
	1.04	40	150.45 ± 4.58	g, h	153.90 ± 4.83	e	153.42 ± 6.91	e, f, g
		60	150.85 ± 4.64	g, h	154.37 ± 4.95	e	154.06 ± 6.96	e, f, g
		80	151.46 ± 4.86	g, h	155.05 ± 5.21	e	155.09 ± 7.12	f, g
	15.04	40	151.24 ± 4.17	g, h	154.55 ± 3.57	e	155.42 ± 3.88	f, g
		60	151.63 ± 4.22	g, h	155.03 ± 3.71	e	155.97 ± 3.99	g
		80	152.24 ± 4.43	g, h	155.70 ± 4.01	e	156.84 ± 4.28	g
UKESM								
FD		40	151.72 ± 2.89	g, h	152.96 ± 4.51	e	155.96 ± 4.20	g
		60	152.11 ± 2.92	g, h	153.35 ± 4.51	e	156.56 ± 4.43	g
		80	152.65 ± 2.97	g, h	153.93 ± 4.51	e	157.59 ± 4.99	g
CD	1.03	40	117.67 ± 4.85	a, b, c, d	120.11 ± 8.54	a	127.00 ± 9.00	a, b
		60	127.29 ± 7.23	b, c, d, e	127.66 ± 12.54	a, b	137.49 ± 9.87	b, c, d
		80	138.38 ± 9.43	e, f, g	137.24 ± 16.30	b, c, d	149.71 ± 9.90	d, e, f, g
	15.03	40	145.71 ± 11.25	g, h	143.50 ± 11.67	c, d, e	153.05 ± 7.87	e, f, g
		60	146.64 ± 11.22	g, h	144.44 ± 11.85	c, d, e	154.11 ± 7.90	e, f, g
		80	148.08 ± 11.13	g, h	145.98 ± 12.28	d, e	155.96 ± 7.99	g
	1.04	40	151.39 ± 6.81	g, h	151.67 ± 8.24	e	157.40 ± 3.54	g
		60	151.85 ± 6.86	g, h	152.17 ± 8.27	e	158.08 ± 3.81	g
		80	152.54 ± 6.94	g, h	153.04 ± 8.42	e	159.31 ± 4.39	g
	15.04	40	152.78 ± 4.35	h	153.66 ± 4.43	e	157.53 ± 3.42	g
		60	153.24 ± 4.40	h	154.14 ± 4.46	e	158.20 ± 3.70	g
		80	153.92 ± 4.46	h	154.94 ± 4.57	e	159.40 ± 4.31	g

Notes: Different letters (a to h) indicate significant differences ($p \leq 0.05$) between variants for each group of years according to Tukey's test.

Starting CD practice on 1 March increases the number of days with GWT above the level of laying drains. For wet years, the number of days for the initial depth of 40 cm b.s.l. was highest at 67, 64, and 60 days for the GFDL, MPI, and UKESM models, respectively (Figure 6A). Also, for a depth of 60 cm b.s.l., it was 63, 60, and 53 days; for a depth of 80 cm b.s.l., it was less than 54 days for the GFDL, MPI, and UKESM models, respectively. The timing of the start of CD practice in normal years indicated a reduction in the number of days. Depending on the initial depth of groundwater when withholding runoff on the 1 March deadline, a range of 37–58 days was indicated for the GFDL model; meanwhile, it was 44–61 for MPI and 45–60 for UKESM (Figure 6B). For dry years, the number of days was 33–54 for GFDL, 40–59 for MPI, and 32–53 for UKESM (Figure 6C). The start of CD practice on 15 March indicates the following time ranges for the GFDL model: 39–41 days, 25–32 days, and 22–28 days for wet, normal and dry years, respectively. For other models including MPI (51–63 days, 44–60 days, and 39–58 days) and UKESM, it was 29–35 days, 32–38 days, and 21–28 days, for wet, normal, and dry years, respectively.

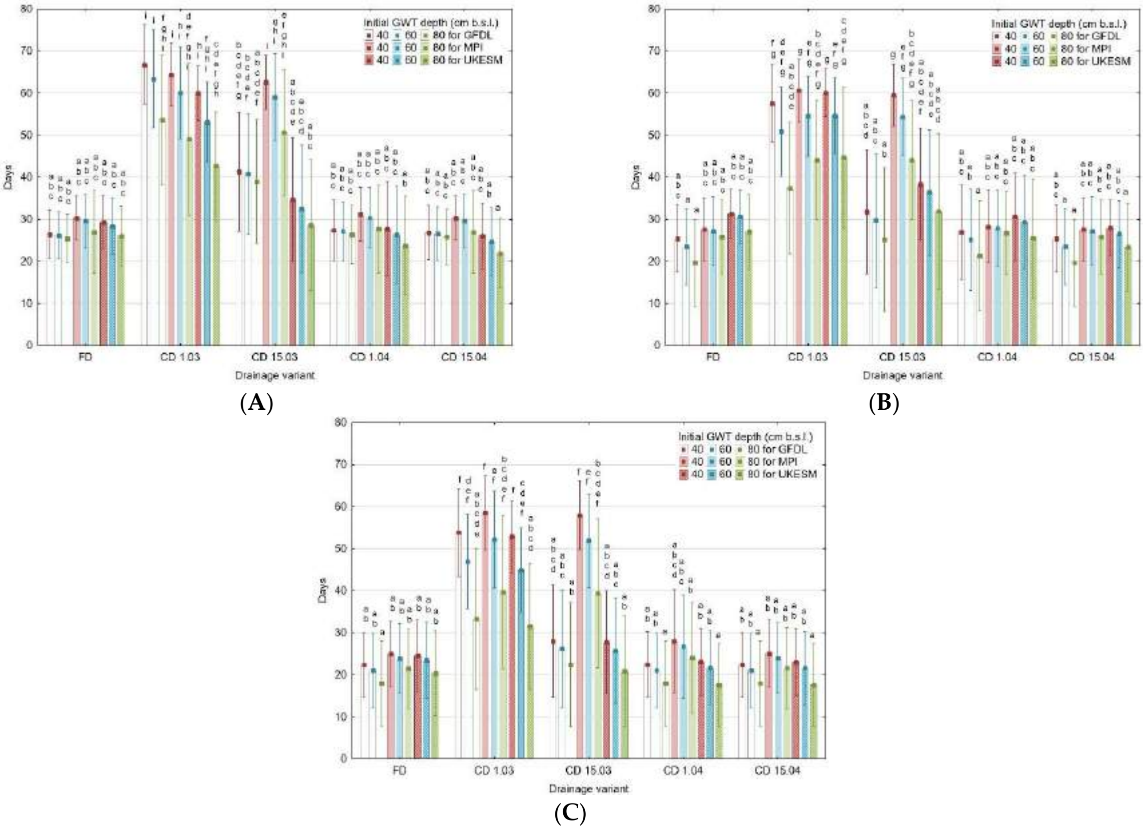

Figure 6. Number of GWT days above the depth of the drainage network under FD and different variants of CD practice for wet (**A**), normal (**B**), and dry (**C**) years for GFDL, MPI, and UKESM climate change models (bar charts show the average values and standard deviation (SD); different letters indicate significant differences ($p \leq 0.05$) between variants of drainage according to the Tukey test).

3.3. Effect of CD on Subsurface Drainage Outflows

The average sum of drainage outflows for the start of the CD on 1 March for the variants of all three rainfall scenarios and the adopted climate change models GFDL, MPI, and UKESM is the lowest value. The obtained modeling results indicate homogeneous groups a and b (Table 5). In addition, for the withholding of outflows on 15 March, for the MPI model, lower outflows were again obtained, indicated for homogeneous groups a–d. Starting CD practice after 1 April and 15 April, the adopted year scenarios do not indicate significant differences for wet, normal, and dry years and are similar to FD results.

Table 5. Average subsurface drainage outflows for wet, normal, and dry years for FD and CD practices of different initial GWT variants for GFDL, MPI, and UKESM climate change models.

Drainage Variants		Initial GWT (cm b.s.l.)	Average Subsurface Drainage Outflows (mm)					
			Wet		Normal		Dry	
GFDL								
FD		40	75.43 ± 14.53	l	51.14 ± 14.01	g, h, i, j	48.64 ± 14.96	j, k, l, m
		60	58.83 ± 14.53	h, i, j, k, l	34.73 ± 13.75	e, f, g, h	32.41 ± 14.50	e, f, g, h, i, j, k, l
		80	40.99 ± 14.46	e, f, g, h, i	17.61 ± 13.00	a, b, c, d, e, f	15.61 ± 13.50	a, b, c, d, e, f, g
CD	1.03	40	1.08 ± 0.20	a	0.95 ± 0.21	a, b	0.97 ± 0.30	a
		60	0.93 ± 0.19	a	0.63 ± 0.16	a, b	0.64 ± 0.20	a
		80	0.72 ± 0.27	a	0.35 ± 0.18	a	0.33 ± 0.20	a
	15.03	40	57.76 ± 10.08	h, i, j, k, l	42.11 ± 6.78	f, g, h, i	41.71 ± 7.52	h, i, j, k, l, m
		60	41.80 ± 9.97	e, f, g, h, i	26.40 ± 6.64	a, b, c, d, e, f, g	26.00 ± 7.29	d, e, f, g, h, i, j
		80	25.01 ± 9.37	a, b, c, d, e, f	10.27 ± 6.04	a, b, c, d, e	9.98 ± 6.53	a, b, c, d, e
	1.04	40	73.99 ± 13.96	l	49.11 ± 11.48	g, h, i, j	48.47 ± 14.82	i, j, k, l, m
		60	57.40 ± 13.97	h, i, j, k, l	32.75 ± 11.23	d, e, f, g	32.27 ± 14.34	e, f, g, h, i, j, k, l
		80	39.60 ± 13.88	d, e, f, g, h, i	15.71 ± 10.49	a, b, c, d, e, f	15.49 ± 13.33	a, b, c, d, e, f
	15.04	40	74.74 ± 13.78	l	51.14 ± 14.01	g, h, i, j	48.64 ± 14.96	j, k, l, m
		60	58.13 ± 13.79	h, i, j, k, l	34.73 ± 13.75	e, f, g, h	32.41 ± 14.50	e, f, g, h, i, j, k, l
		80	40.30 ± 13.72	e, f, g, h, i	17.61 ± 13.00	a, b, c, d, e, f	15.61 ± 13.50	a, b, c, d, e, f, g
MPI								
FD		40	71.70 ± 23.40	k, l	64.33 ± 17.92	i, j	58.13 ± 22.29	m
		60	55.05 ± 23.35	g, h, i, j, k, l	47.76 ± 17.65	g, h, i, j	41.74 ± 22.22	h, i, j, k, l, m
		80	37.33 ± 22.99	c, d, e, f, g, h	30.12 ± 17.10	d, e, f, g	24.41 ± 21.88	b, c, d, e, f, g, h
CD	1.03	40	1.10 ± 0.24	a	1.04 ± 0.22	a, b	0.96 ± 0.33	a
		60	0.91 ± 0.28	a	0.75 ± 0.23	a, b	0.67 ± 0.20	a
		80	0.56 ± 0.36	a	0.47 ± 0.21	a, b	0.37 ± 0.14	a
	15.03	40	13.19 ± 12.89	a, b, c	6.41 ± 8.36	a, b, c, d	4.91 ± 8.94	a, b, c, d
		60	6.00 ± 9.11	a, b	2.83 ± 4.98	a, b, c	2.69 ± 6.24	a, b, c
		80	2.14 ± 4.85	a	0.99 ± 1.82	a, b	1.46 ± 3.42	a, b
	1.04	40	70.38 ± 21.96	j, k, l	63.36 ± 16.22	i, j	54.89 ± 21.63	l, m
		60	53.73 ± 21.91	g, h, i, j, k, l	46.80 ± 15.93	g, h, i, j	38.64 ± 21.48	g, h, i, j, k, l, m
		80	36.02 ± 21.55	c, d, e, f, g, h	29.17 ± 15.35	c, d, e, f, g	21.86 ± 20.98	a, b, c, d, e, f, g, h
	15.04	40	71.70 ± 23.40	k, l	64.33 ± 17.92	i, j	58.11 ± 22.27	m
		60	55.05 ± 23.35	g, h, i, j, k, l	47.76 ± 17.65	g, h, i, j	41.72 ± 22.19	h, i, j, k, l, m
		80	37.33 ± 22.99	c, d, e, f, g, h	30.12 ± 17.10	d, e, f, g	24.39 ± 21.86	b, c, d, e, f, g, h
UKESM								
FD		40	62.96 ± 14.71	i, j, k, l	69.67 ± 25.55	j	51.20 ± 12.62	k, l, m
		60	46.27 ± 14.66	e, f, g, h, i, j	52.98 ± 25.50	g, h, i, j	34.82 ± 12.18	f, g, h, i, j, k, l
		80	28.41 ± 14.54	b, c, d, e, f	35.16 ± 25.32	e, f, g, h	17.71 ± 11.18	a, b, c, d, e, f, g
CD	1.03	40	1.20 ± 0.31	a	1.06 ± 0.26	a, b	0.98 ± 0.30	a
		60	0.82 ± 0.27	a	0.79 ± 0.31	a, b	0.64 ± 0.18	a
		80	0.49 ± 0.21	a	0.50 ± 0.28	a, b	0.34 ± 0.19	a
	15.03	40	47.27 ± 10.12	f, g, h, i, j, k	47.31 ± 14.32	g, h, i, j	41.05 ± 8.02	i, j, k, l, m
		60	31.44 ± 9.87	c, d, e, f, g	31.56 ± 14.05	d, e, f, g	25.40 ± 7.78	c, d, e, f, g, h, i
		80	15.03 ± 9.14	a, b, c, d	15.35 ± 13.31	a, b, c, d, e	9.60 ± 6.93	a, b, c, d, e
	1.04	40	56.05 ± 10.25	g, h, i, j, k, l	60.87 ± 23.10	h, i, j	47.94 ± 11.61	h, i, j, k, l, m
		60	39.47 ± 10.18	d, e, f, g, h, i	44.37 ± 22.88	g, h, i, j	31.69 ± 11.11	e, f, g, h, i, j, k
		80	21.85 ± 9.94	a, b, c, d, e	27.04 ± 22.21	b, c, d, e, f, g	14.91 ± 9.93	a, b, c, d, e, f
	15.04	40	58.40 ± 13.39	h, i, j, k, l	64.63 ± 25.22	i, j	48.15 ± 11.66	i, j, k, l, m
		60	41.81 ± 13.30	e, f, g, h, i	48.07 ± 25.04	g, h, i, j	31.88 ± 11.17	e, f, g, h, i, j, k, l
		80	24.16 ± 13.04	a, b, c, d, e, f	30.60 ± 24.47	d, e, f, g	15.05 ± 10.02	a, b, c, d, e, f

Notes: Different letters (a to l) indicate significant differences ($p \leq 0.05$) between variants for each group of years according to Tukey's test.

The lowest number of days with drainage runoff was indicated when the practice of stopping runoff began on 1 March for all modeling scenarios (Figure 7). In wet years, for the adopted scenarios, the number of days with drainage outflow is 17–19, 18–21 and 15 for the GFDL, MPI, and UKESM models, respectively. In normal years, it is 12–14, 15–17, and 16–18 days for the GFDL, MPI, and UKESM models, respectively. Similarly, in dry years, it is 12–14, 13–15, and 11–13 days for the GFDL, MPI, and UKESM models, respectively.

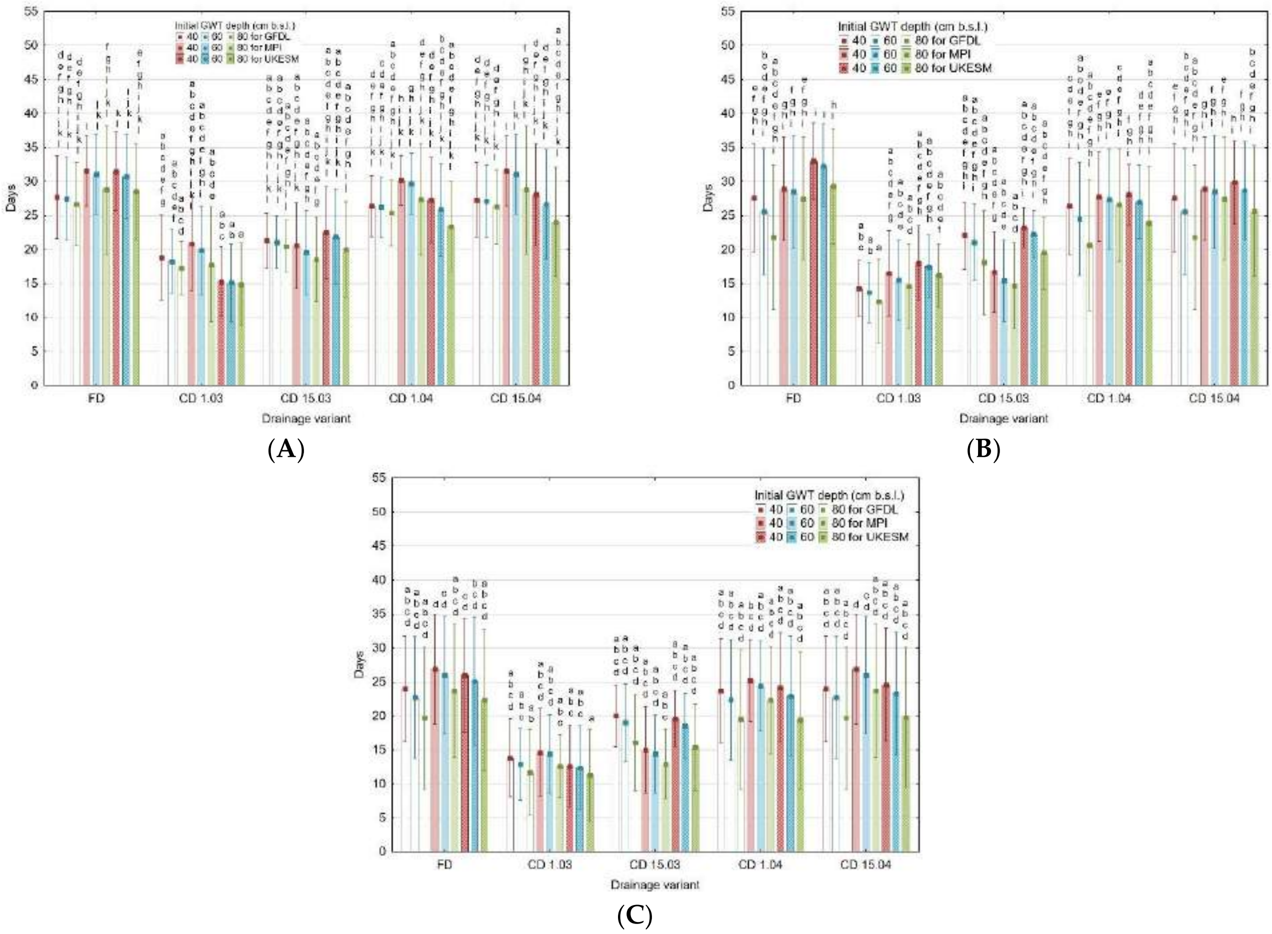

Figure 7. Number of days with drainage outflow for FD and different variants of CD practice under wet (**A**), normal (**B**), and dry (**C**) years for GFDL, MPI, and UKESM climate change models (bar charts show the average values and SD; different letters indicate significant differences ($p \leq 0.05$) between variants of drainage according to the Tukey test).

The greatest reduction in outflows was obtained at the 1 March start date of the CD practice for all assumed modeling scenarios (Figure 8). Regardless of the assumed initial GWT in wet, normal, and dry years, the reduction results obtained were 100%. Moving the date to two weeks later (15 March) yields a significant reduction for the MPI model (above 85%). At this date, the other two models indicate much lower reductions, at 10–55%. The later withholding of outflows from 1 April to 15 April indicates the lowest reductions and/or none at all. No effect was observed when outflows were blocked from 15 April onwards for the GFDL and MPI models.

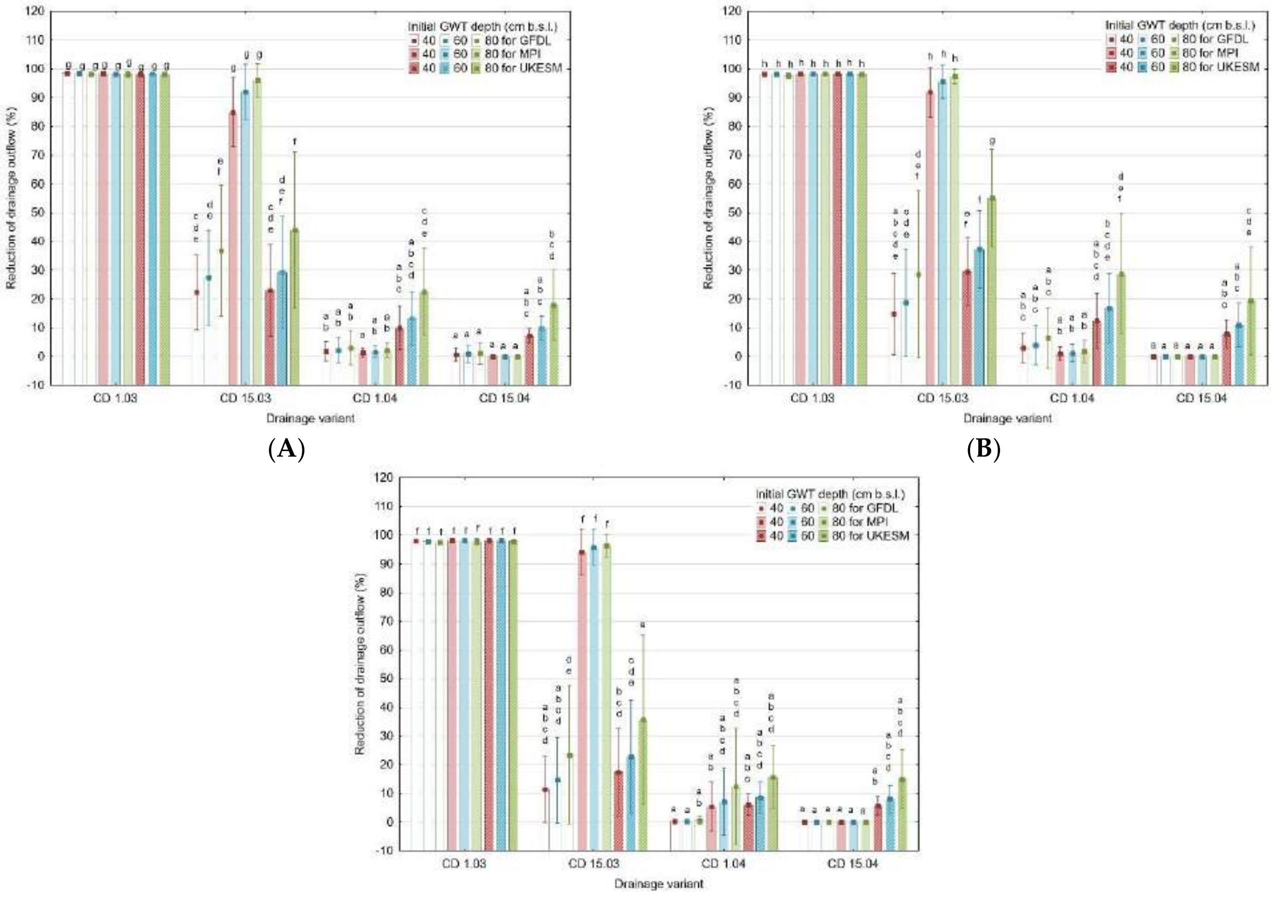

Figure 8. Reduction in drainage outflow for different variants of CD practice under wet (**A**), normal (**B**), and dry (**C**) years for GFDL, MPI, and UKESM climate change models (bar charts show the average values and SD; different letters indicate significant differences ($p \leq 0.05$) between variants of drainage according to the Tukey test).

3.4. Effect of CD on Surface Runoff

The highest average values of surface runoff are shown for the GFDL model for wet years with the 1 March CD start date (above 30 mm) (Figure 9). In most scenarios, for each initial GWT and different year variant, the results obtained are similar regardless of the model of predicted climate change. For normal years, the GFDL and UKESM models for all modeling scenarios indicate the same surface runoff value of 25 mm, except for the 1 March date. In dry years, significantly lower values of surface runoff were obtained, with identical results for FD and CD started on 1 April and 15 April for all scenarios for each model.

3.5. Effect of CD on Quality Drainage Outflow

The results of the analysis of the NO_3–N loads carried out indicate a significant reduction in the amount of carried loads when CD began on 1 March in all scenarios for the three climate models (Table 6). This confirms the classification of this date into two homogeneous groups a and b with a range from 0.11 to 0.51 kg ha^{-1}. Also, the lowest values of loads were shown for the 15 March date for the MPI model, with a range from 0.42 to 5.58 kg ha^{-1}. The CD technique that started on 1 March reduced load leaching by an average of 24.34, 22.79, and 19.06 kg ha^{-1} compared to FD in wet years for the GFDL, MPI, and UKESM models, respectively. In contrast, in normal years, the average load was 14.33, 19.74, and 21.93 kg ha^{-1}, and, in dry years, it was 13.36, 17.25, and 14.36 kg ha^{-1} for the GFDL, MPI, and UKESM models, respectively. The start of withholding outflow after the 1 April and 15 April dates did not reduce the amount of NO_3–N loads leached.

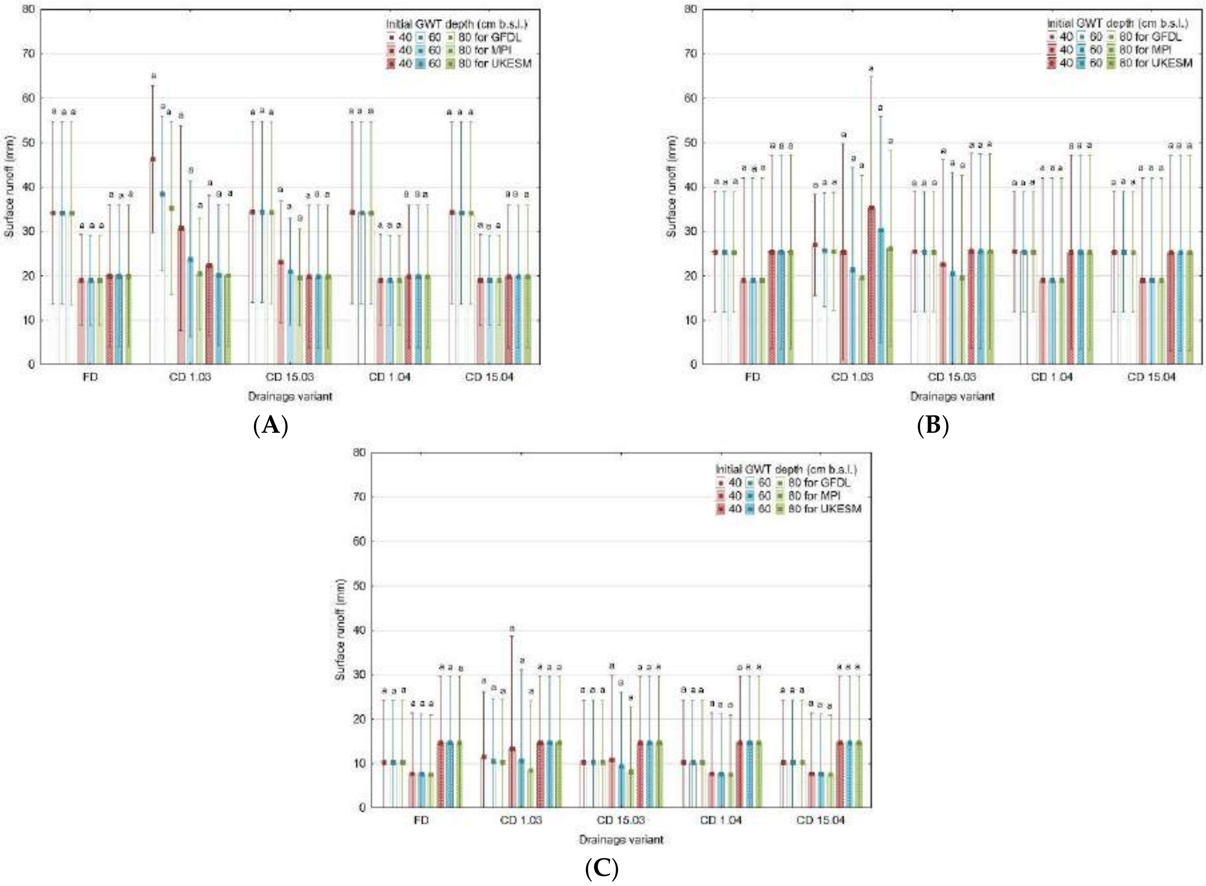

Figure 9. Surface runoff for FD and different variants of CD practice and GFDL, MPI, and UKESM climate change models under wet (**A**), normal (**B**), and dry (**C**) years (bar charts show the average values and SD; different letters indicate significant differences ($p \leq 0.05$) between variants of drainage according to the Tukey test).

Table 6. Average NO_3–N (kg ha^{-1}) loads for wet, normal, and dry years for GFDL, MPI, and UKESM climate change models.

Drainage Variants		**Initial GWT (cm b.s.l.)**	**Load NO_3–N (kg ha^{-1})**					
			Wet		**Normal**		**Dry**	
GFDL								
FD		40	31.93	l	21.64	g, h, i, j	20.59	j, k, l, m
		60	24.90	h, i, j, k, l	14.70	e, f, g, h	13.72	e, f, g, h, i, j, k, l
		80	17.35	e, f, g, h, i	7.45	a, b, c, d, e, f	6.61	a, b, c, d, e, f, g
CD	1.03	40	0.46	a	0.40	a, b	0.41	a
		60	0.39	a	0.27	a, b	0.27	a
		80	0.30	a	0.15	a	0.14	a
	15.03	40	24.45	h, i, j, k, l	17.82	f, g, h, i	17.66	h, i, j, k, l, m
		60	17.69	e, f, g, h, i	11.17	a, b, c, d, e, f, g	11.01	d, e, f, g, h, i, j
		80	10.59	a, b, c, d, e, f	4.35	a, b, c, d, e	4.23	a, b, c, d, e
	1.04	40	31.32	l	20.78	g, h, i, j	20.52	i, j, k, l, m
		60	24.29	h, i, j, k, l	13.86	d, e, f, g	13.66	e, f, g, h, i, j, k, l
		80	16.76	d, e, f, g, h, i	6.65	a, b, c, d, e, f	6.56	a, b, c, d, e, f
	15.04	40	31.63	l	21.64	g, h, i, j	20.59	j, k, l, m
		60	24.61	h, i, j, k, l	14.70	e, f, g, h	13.72	e, f, g, h, i, j, k, l
		80	17.06	e, f, g, h, i	7.45	a, b, c, d, e, f	6.61	a, b, c, d, e, f, g

Table 6. *Cont.*

Drainage Variants		Initial GWT (cm b.s.l.)	Load NO_3–N (kg ha^{-1})					
			Wet		Normal		Dry	
MPI								
FD		40	30.35	k, l	27.23	i, j	24.61	m
		60	23.30	g, h, i, j, k, l	20.21	g, h, i, j	17.67	h, i, j, k, l, m
		80	15.80	c, d, e, f, g, h	12.75	d, e, f, g	10.33	b, c, d, e, f, g, h
CD	1.03	40	0.47	a	0.44	a, b	0.41	a
		60	0.38	a	0.32	a, b	0.28	a
		80	0.24	a	0.20	a, b	0.16	a
	15.03	40	5.58	a, b, c	2.71	a, b, c, d	2.08	a, b, c, d
		60	2.54	a, b	1.20	a, b, c	1.14	a, b, c
		80	0.91	a	0.42	a, b	0.62	a, b
	1.04	40	29.79	j, k, l	26.82	i, j	23.23	l, m
		60	22.74	g, h, i, j, k, l	19.81	g, h, i, j	16.35	g, h, i, j, k, l, m
		80	15.25	c, d, e, f, g, h	12.35	c, d, e, f, g	9.14	a, b, c, d, e, f, g, h
	15.04	40	30.35	k, l	27.23	i, j	24.60	m
		60	23.30	g, h, i, j, k, l	20.21	g, h, i, j	17.66	h, i, j, k, l, m
		80	15.80	c, d, e, f, g, h	12.75	d, e, f, g	10.32	b, c, d, e, f, g, h
UKESM								
FD		40	26.65	i, j, k, l	29.49	j	21.67	k, l, m
		60	19.58	e, f, g, h, i, j	22.43	g, h, i, j	14.74	f, g, h, i, j, k, l
		80	12.03	b, c, d, e, f	14.88	e, f, g, h	7.50	a, b, c, d, e, f, g
CD	1.03	40	0.51	a	0.45	a, b	0.41	a
		60	0.35	a	0.33	a, b	0.27	a
		80	0.21	a	0.21	a, b	0.14	a
	15.03	40	20.01	f, g, h, i, j, k	20.03	g, h, i, j	17.38	h, i, j, k, l, m
		60	13.31	c, d, e, f, g	13.36	d, e, f, g	10.75	c, d, e, f, g, h, i
		80	6.36	a, b, c, d	6.50	a, b, c, d, e	4.06	a, b, c, d, e
	1.04	40	23.72	g, h, i, j, k, l	25.77	h, i, j	20.29	i, j, k, l, m
		60	16.71	d, e, f, g, h, i	18.78	g, h, i, j	13.41	e, f, g, h, i, j, k
		80	9.25	a, b, c, d, e	11.44	b, c, d, e, f, g	6.31	a, b, c, d, e, f
	15.04	40	24.72	h, i, j, k, l	27.35	i, j	20.38	i, j, k, l, m
		60	17.10	e, f, g, h, i	20.35	g, h, i, j	13.49	e, f, g, h, i, j, k, l
		80	10.23	a, b, c, d, e, f	12.95	d, e, f, g	6.37	a, b, c, d, e, f

Notes: Different letters (a to l) indicate significant differences ($p \leq 0.05$) between variants for each group of years according to Tukey's test.

Holding the outflow on the date of 1 March significantly reduced the amount of PO_4 load lifted from the site compared to FD. Two homogeneous groups, a and b (Table 7), were determined for each scenario, considering this date for all climate models. For the MPI model, significantly lower loads were also obtained on the 15 March date.

The highest reduction close to 100% of NO_3–N and PO_4 loads was shown for the CD application on 1 March (Table 8) for all GFDL, MPI, and UKESM models. Also, for the MPI model, starting the withholding of outflow on 15 March shows reductions of 85% or more for wet, normal, and dry years. Starting CD practice on 1 April and 15 April shows a much lower or no reduction.

Table 7. Average PO_4 (kg ha^{-1}) loads for wet, normal, and dry years for GFDL, MPI, and UKESM models.

Drainage Variants		Initial GWT (cm b.s.l.)	Load PO_4 (kg ha^{-1})					
			Wet		Normal		Dry	
GFDL								
FD		40	1.25	l	0.85	g, h, i, j	0.81	j, k, l, m
		60	0.98	h, i, j, k, l	0.58	e, f, g, h	0.54	e, f, g, h, i, j, k, l
		80	0.68	e, f, g, h, i	0.29	a, b, c, d, e, f	0.26	a, b, c, d, e, f, g
CD	1.03	40	0.02	a	0.02	a, b	0.02	a
		60	0.02	a	0.01	a, b	0.01	a
		80	0.01	a	0.01	a	0.01	a
	15.03	40	0.96	h, i, j, k, l	0.70	f, g, h, i	0.69	h, i, j, k, l, m
		60	0.69	e, f, g, h, i	0.44	a, b, c, d, e, f, g	0.43	d, e, f, g, h, i, j
		80	0.42	a, b, c, d, e, f	0.17	a, b, c, d, e	0.17	a, b, c, d, e
	1.04	40	1.23	l	0.82	g, h, i, j	0.80	i, j, k, l, m
		60	0.95	h, i, j, k, l	0.54	d, e, f, g	0.54	e, f, g, h, i, j, k, l
		80	0.66	d, e, f, g, h, i	0.26	a, b, c, d, e, f	0.26	a, b, c, d, e, f
	15.04	40	1.24	l	0.85	g, h, i, j	0.81	j, k, l, m
		60	0.97	h, i, j, k, l	0.58	e, f, g, h	0.54	e, f, g, h, i, j, k, l
		80	0.67	e, f, g, h, i	0.29	a, b, c, d, e, f	0.26	a, b, c, d, e, f, g
MPI								
FD		40	1.19	k, l	1.07	i, j	0.97	m
		60	0.91	g, h, i, j, k, l	0.79	g, h, i, j	0.69	h, i, j, k, l, m
		80	0.62	c, d, e, f, g, h	0.50	d, e, f, g	0.41	b, c, d, e, f, g, h
CD	1.03	40	0.02	a	0.02	a, b	0.02	a
		60	0.02	a	0.01	a, b	0.01	a
		80	0.01	a	0.01	a, b	0.01	a
	15.03	40	0.22	a, b, c	0.11	a, b, c, d	0.08	a, b, c, d
		60	0.10	a, b	0.05	a, b, c	0.04	a, b, c
		80	0.04	a	0.02	a, b	0.02	a, b
	1.04	40	1.17	j, k, l	1.05	i, j	0.91	l, m
		60	0.89	g, h, i, j, k, l	0.78	g, h, i, j	0.64	g, h, i, j, k, l, m
		80	0.60	c, d, e, f, g, h	0.48	c, d, e, f, g	0.36	a, b, c, d, e, f, g, h
	15.04	40	1.19	k, l	1.07	i, j	0.96	m
		60	0.91	g, h, i, j, k, l	0.79	g, h, i, j	0.69	h, i, j, k, l, m
		80	0.62	c, d, e, f, g, h	0.50	d, e, f, g	0.40	b, c, d, e, f, g, h
UKESM								
FD		40	1.05	i, j, k, l	1.16	j	0.85	k, l, m
		60	0.77	e, f, g, h, i, j	0.88	g, h, i, j	0.58	f, g, h, i, j, k, l
		80	0.47	b, c, d, e, f	0.58	e, f, g, h	0.29	a, b, c, d, e, f, g
CD	1.03	40	0.02	a	0.02	a, b	0.02	a
		60	0.01	a	0.01	a, b	0.01	a
		80	0.01	a	0.01	a, b	0.01	a
	15.03	40	0.78	f, g, h, i, j, k	0.79	g, h, i, j	0.68	h, i, j, k, l, m
		60	0.52	c, d, e, f, g	0.52	d, e, f, g	0.42	c, d, e, f, g, h, i
		80	0.25	a, b, c, d	0.25	a, b, c, d, e	0.16	a, b, c, d, e
	1.04	40	0.93	g, h, i, j, k, l	1.01	h, i, j	0.80	i, j, k, l, m
		60	0.66	d, e, f, g, h, i	0.74	g, h, i, j	0.53	e, f, g, h, i, j, k
		80	0.36	a, b, c, d, e	0.45	b, c, d, e, f, g	0.25	a, b, c, d, e, f
	15.04	40	0.97	h, i, j, k, l	1.07	i, j	0.80	i, j, k, l, m
		60	0.69	e, f, g, h, i	0.80	g, h, i, j	0.53	e, f, g, h, i, j, k, l
		80	0.40	a, b, c, d, e, f	0.51	d, e, f, g	0.25	a, b, c, d, e, f

Notes: Different letters (a to l) indicate significant differences ($p \leq 0.05$) between variants for each group of years according to Tukey's test.

Table 8. NO_3–N and PO_4 reduction for different variants of CD practice in wet, normal, and dry years for GFDL, MPI, and UKESM models.

Drainage Variants		Initial GWT (cm b.s.l.)	Reduction in NO_3–N and PO_4 (%)					
			Wet		Normal		Dry	
GFDL								
CD	1.03	40	98.51	g	98.09	h	98.00	f
		60	98.40	g	98.06	h	97.94	f
		80	98.23	g	97.58	h	97.49	f
	15.03	40	22.39	c, d, e	14.85	a, b, c, d, e	11.42	a, b, c, d
		60	27.51	d, e	18.85	c, d, e	14.73	a, b, c, d
		80	36.86	e, f	28.62	d, e, f	23.53	d, e
	1.04	40	1.78	a, b	3.06	a, b, c	0.31	a
		60	2.25	a, b	4.04	a, b, c	0.36	a
		80	3.15	a, b	6.39	a, b, c	0.64	a, b
	15.04	40	0.75	a	0.00	a	0.00	a
		60	0.92	a	0.00	a	0.00	a
		80	1.20	a	0.00	a	0.00	a
MPI								
CD	1.03	40	98.37	g	98.32	h	98.15	f
		60	98.23	g	98.35	h	98.06	f
		80	98.19	g	98.26	h	97.76	f
	15.03	40	85.02	g	91.97	h	94.14	f
		60	92.09	g	95.67	h	95.89	f
		80	95.99	g	97.45	h	96.33	f
	1.04	40	1.41	a	1.05	a, b	5.32	a, b
		60	1.72	a, b	1.30	a, b	7.18	a, b, c, d
		80	2.25	a, b	1.76	a, b	12.48	a, b, c, d
	15.04	40	0.00	a	0.00	a	0.02	a
		60	0.00	a	0.00	a	0.03	a
		80	0.00	a	0.00	a	0.04	a
UKESM								
CD	1.03	40	98.09	g	98.31	h	98.10	f
		60	98.21	g	98.33	h	98.12	f
		80	98.14	g	98.24	h	97.92	f
	15.03	40	22.96	c, d, e	29.51	e, f	17.42	b, c, d
		60	29.22	d, e, f	37.27	f	22.80	c, d, e
		80	43.92	f	55.25	g	35.73	e
	1.04	40	9.96	a, b, c	12.48	a, b, c, d	6.13	a, b, c
		60	13.26	a, b, c, d	16.80	b, c, d, e	8.62	a, b, c, d
		80	22.48	c, d, e	28.84	d, e, f	15.67	a, b, c, d
	15.04	40	7.22	a, b, c	7.98	a, b, c	5.73	a, b
		60	9.87	a, b, c	10.98	a, b, c	8.10	a, b, c, d
		80	17.97	b, c, d	19.34	c, d, e	14.94	a, b, c, d

Notes: Different letters (a to f) indicate significant differences ($p \leq 0.05$) between variants for each group of years according to Tukey's test.

4. Discussion

Based on the results, the analysis of withholding outflow on the drainage network for the SSP370 pathway in the near future indicates that the efficiency of using CD solutions will increase compared to the present state. Withholding outflow on 1 March allows GWT to increase by an average of 35, 23, and 21 cm for the GFDL climate change model, by 31, 28, and 25 cm for MPI, and by 24, 25, and 19 cm for UKESM in wet, normal, and dry years, respectively, compared to FD. Comparing the present climate conditions [34] to the near future using CD on 1 March, the highest increase in GWT was achieved for the GFDL and MPI models for wet years of 4 to 8% and 3 to 6%, respectively, and for initial depths of 40 and 80 cm b.s.l. Similarly, the highest increases in GWT were recorded for the MPI model on 15 March for wet, normal, and dry years, ranging from 10–19%, 7–18%, and 2–15%, respectively. These highest values refer to the initial water depth of 40 cm b.s.l. According to the UKESM model results for the CD practice started on 1 and 15 March, no significant increases or decreases of ±2% were observed. Thus, the number of days with GWT above the drainage level (>90 cm) increases. In wet years, the number of days for the initial depth of 40 cm b.s.l. was the highest, with 67, 64, and 60 days for the GFDL, MPI, and UKESM models, respectively. For a depth of 60 cm b.s.l., it was 63, 60, and 53 days, while, for 80 cm b.s.l., it was less than 54 days for the GFDL, MPI, and UKESM models, respectively. Sojka et al. [30], who simulated the impact of CD from March to September with RCP 4.5, found that blocking outflow at the 1 March date in the near-future GWT will maintain an average of 85 days regarding the drain level.

The average sum of the drainage outflows for CD started on 1 March, allowing them to be reduced, compared to FD, by 52 mm (58, 54, and 45 mm for wet years), by 44 mm (34, 47, and 52 mm for normal years), and by 35 mm (32, 41, and 34 mm for dry years) based on the results of the three models. The lowest number of days with outflow is 17–19, 18–21 and 15 days in wet years for the GFDL, MPI, and UKESM models, respectively. In normal years, it is 12–14, 15–17, and 16–18 days, and, in dry years, it is 12–14, 13–15, and 11–13 days for the GFDL, MPI, and UKESM models, respectively. Relative to the actual climate conditions given by Kęsicka et al. [34], the highest average outflow increase of 33–80% was modeled for the near future according to the GFDL model using CD on 1 March, with GWT initial depths of 60 and 80 cm b.s.l. The MPI and UKESM models showed increases of 30–40% and 7–18%, respectively, for wet years and 17–23% and 13–25%, respectively, for normal years, both with initial depths of 60 and 80 cm b.s.l. On the other hand, when the outflow was stopped on 15 March for the MPI model in all three wet, normal, and dry years, reductions of 69–79%, 85–91%, and 88–90% were obtained. Regardless of the initial GWT in wet, normal, and dry years, the resulting reductions were 100%. Moving the date to two weeks later (15 March) yields a significant reduction for the MPI model above 85%. At this date, the other two models indicate much lower reductions, at 10–55%. Stopping the outflows from 1 April to 15 April indicates the lowest reductions and/or no reductions at all. Using CD on 1 March allows for lower amounts of NO_3–N in wet years (on average, 22 kg per ha), as well as 19 kg per ha in normal years and 15 kg per ha in dry years. For PO_4, it is 0.9, 0.7, and 0.6 kg per ha for wet, normal, and dry years. Sojka et al. [30] indicated an average reduction in outflow at the start of CD on the 1 March at an average level of 82% and 84% in the near and far future for the drainage networks with a spacing of 7 m. However, that research has shown that there will be a decrease in outflows from the drainage network in the analyzed time period, along with an increase in precipitation in that period. Pease et al. [33] have indicated that CD efficiency was projected to increase during summer by a 42.7% and 81.8% reduction in subsurface drainage outflow for RCP 4.5 and RCP 8.5 under late-century climate conditions. According to Khalil et al. [47], the role of CD in paddy field simulations showed a significant decrease of 61% in the drainage discharge in the near future for RCP 8.5. These results further showed that there would be a 99% decrease in runoff rate in scenarios under RCP 8.5 in the near future. Other results have shown that, under future climate change conditions, the subsurface outflow will increase, along with an increasing mean yearly precipitation [48–50].

Selected climate change design models for precipitation showed an increase in the average value of surface runoff for the GFDL model for wet years on the 1 March CD start date (above 30 mm). For normal years, the GFDL and UKESM models for all modeling scenarios indicate the same value of 25 mm of surface runoff, except for the 1 March date. In dry years, much lower values of surface runoff were obtained. CD starting on 1 April and 15 April, for all scenarios, for each model, had identical results to FD. According to Kęsicka et al. [34], surface runoff for current climate conditions is approximately 4.4 mm, 1.0 mm, and 0.4 mm for wet, normal, and dry years, respectively. Comparing these values to the obtained results for future climate conditions, a significant increase was noted in all models. The largest increase was observed for wet years using CD on 1 March, with values ranging between 31–42 mm, 16–26 mm, and 16–18 mm for the GFDL, MPI, and UKESM models, respectively. However, the smallest increase was observed for dry years, with values ranging from 8 to 14 mm for the adopted models. When CD is applied on 15 March for wet years, there is an increase of 30 mm, 15–19 mm, and 16 mm for the GFDL, MPI, and UKESM models, respectively. Sojka et al. [30] have shown that, in the near future, outflows measure 9.5 mm on average and that, in the far future, they measure 9.0 mm on average. These values are almost five times higher than at the present time, due to the increase in rainfall intensity in the near and far future. Mehan et al. [51] indicate that the potential growth of surface runoff should be taken into account in the future. This is important because more nutrient losses have been predicted due to extreme precipitation events with surface outflow. However, Awad et al. [52] have shown that surface runoff will be reduced by 25.3% and 23.6% under RCP 4.5 and 8.5 climate scenarios, respectively. Also, Singh et al. [53] indicated that, according to the same trend, a roughly 10–21% reduction is observed in the average annual surface runoff under future climatic scenarios.

The results obtained represent CD efficiency depending on the selected time of the simulations carried out. According to the adopted SSP370 path, an increase in average rainfall for the analyzed time period is indicated. In addition, the results presented depend on the basic parameters characterizing the drainage object, including geological conditions, soil conditions, topography, drainage network parameters, as well as hydrological and meteorological conditions. The results of this simulation show the potential hydrological impact of CD on an area in central Wielkopolska under varying meteorological forces using three models from a range of possible future climate scenarios. Thus, the results should not be interpreted as a strict forecast for the future. Moreover, in the future, vegetation can start earlier due to higher temperatures.

5. Conclusions

The results of the simulations of two FD and CD methods affecting water management in a drainage facility in the near future over a period of 30 years made it possible to analyze the impact of CD on water balance and the GWT under different conditions of the predicted climate changes of the GFDL, MPI, and UKESM models. Based on the simulated scenarios, the following conclusions were made:

1. The results indicated that the earliest start of CD practice is the most effective in increasing GWT. In the near future, starting CD practice on 1 March will increase the average GWT by 24–35, 23–28, and 19–25 cm for wet, normal, and dry years for selected climate change prediction models compared to the FD practice. Compared to present climate conditions, the application of CD with an initial GWT of 40 cm b.s.l. will raise water depths by 4% in the near future. In contrast, comparing the start of the CD practice to 15 March, there will be a 2% average GWT rise in the near future;
2. The earliest application of CD on 1 March reduced average annual outflow by 52, 44, and 35 mm for wet, normal, and dry years, respectively. Compared to current climatic conditions, when applying CD on 1 March in the near future with an initial GWT of 60 and 80 cm b.s.l. in wet years, drainage outflows will increase by 33% and 80% for the GFDL model, by 30% and 40% for the MPI model, and by 17% and 23% for the UKESM model. These are the results of the increase in the total precipitation predicted by the models for 2021–2050;
3. Comparing the surface runoff values obtained to current climate conditions, the MPI, GFDL, and UKESM models predict a significant increase in surface runoff in the near future, which is due to a predicted increase in precipitation. The GFDL model shows surface runoff above 30 mm for all scenarios in wet years. For normal years, the GFDL and UKESM models show a value of 25 mm; meanwhile, the MPI model shows

20 mm. In dry years, the models indicate lower surface runoff values of less than 15 mm;

4. Annual NO_3–N was reduced by 22, 19, and 15 kg per hectare for wet, normal, and dry years, respectively, in the near future. Among the climate scenarios, the UKESM model predicted higher NO_3–N and PO_4 leaching values compared to the MPI and GFDL models. The highest reduction close to 100% of the NO_3–N and PO_4 loads was shown for CD application compared to FD on 1 March due to a reduction in drainage outflow. For the 15 March CD date, individual climate models indicated much greater variability in nutrient reduction.

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9. Oświadczenia doktoranta i współautorów

Oświadczenie autora pracy doktorskiej o jej oryginalności, samodzielności jej przygotowania i o nienaruszeniu praw autorskich

Barbara Kęsicka
imię i nazwisko doktoranta

Niniejszym oświadczam, że przedłożoną pracę doktorską pt.: *Wpływ sterowania odpływem drenarskim na wybrane elementy gospodarki wodnej gleb i straty azotu na obszarze zdrenowanym*
napisałem samodzielnie, tj.

- nie zleciłem opracowania pracy lub jej części innym osobom,
- nie przepisałem pracy lub jej części z innych opracowań i prac związanych tematycznie z moją pracą,
- korzystałem jedynie z niezbędnych konsultacji,
- wszystkie elementy pracy, które zostały wykorzystane do jej realizacji (cytaty, ryciny, tabele, programy itp.), a nie będące mojego autorstwa, zostały odpowiednio zaznaczone oraz zostało podane źródło ich pochodzenia,
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Mam świadomość, że złożenie nieprawdziwego oświadczenia skutkować będzie niedopuszczeniem do dalszych czynności przewodu doktorskiego lub cofnięciem decyzji o nadaniu mi stopnia doktora oraz wszczęciem postępowania dyscyplinarnego.

17.11.2023 r. Barbara Kęsicka
data i czytelny podpis autora

Oświadczenie autora o zgodności elektronicznej wersji pracy z jej formą wydrukowaną

Barbara Kęsicka
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Niniejszym oświadczam, że załączona, wydrukowana wersja mojej pracy doktorskiej pt. *Wpływ sterowania odpływem drenarskim na wybrane elementy gospodarki wodnej gleb i straty azotu na obszarze zdrenowanym* jest zgodna z plikiem w wersji elektronicznej, znajdującym się na załączonym nośniku, przeznaczonym do sprawdzenia w systemie antyplagiatowym.

17.11.2023 r. Barbara Kęsicka
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Oświadczenie promotorów rozprawy doktorskiej

Oświadczamy, że niniejsza rozprawa została przygotowana pod naszym kierunkiem i stwierdzamy, że spełnia ona warunki do przedstawienia jej w postępowaniu o nadanie stopnia naukowego.

Data 23.11.2023

Podpis promotora rozprawy ....

Podpis promotora pomocniczego rozprawy ....

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy *Kęsicka B., Stasik R., Kozłowski M. (2022). Effects of modelling studies on controlled drainage in agricultural land on reduction of outflow and nitrate losses–a meta-analysis. PLOS ONE, 17(4), e0267736. DOI: 10.1371/journal.pone.0267736.* mój indywidualny udział w jej powstaniu polegał na opracowaniu koncepcji badań, zebraniu literatury przedmiotowej, przeprowadzeniu obliczeń statystycznych dla wykonanych metaanaliz, analizie i interpretacji danych, wskazaniu metodyki, wykonaniu rycin, napisaniu i redakcji manuskryptu, przygotowaniu odpowiedzi w procesie recenzji artykułu, co stanowi 60% całej pracy.

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy *Kęsicka B., Kozlowski M., Stasik R. (2023). Effectiveness of Controlled Tile Drainage in Reducing Outflow and Nitrogen at the Scale of the Drainage System. Water, 15, 1814. DOI: 10.3390/w15101814.* mój indywidualny udział w jej powstaniu polegał na opracowaniu koncepcji artykułu, wskazaniu metodologii badań, zebraniu materiału badawczego, wykonaniu analiz fizyczno-chemicznych pobranych próbek, zebraniu literatury przedmiotu, przeprowadzeniu badań modelowych, analizie i interpretacji danych, wykonaniu obliczeń statystycznych, napisaniu i redakcji manuskryptu, przygotowaniu rycin, przygotowaniu odpowiedzi w procesie recenzji artykułu, co stanowi 70% całej pracy.

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Oświadczenie o współautorstwie

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Oświadczenie o współautorstwie

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy *Kęsicka B., Kozłowski M., Stasik R., Pińskwar I. (2023). Controlled Drainage Effectiveness in Reducing Nutrient Outflow in Light of Climate Changes. Applied Sciences, 13 (16), 9077. DOI: 10.3390/app13169077.* mój indywidualny udział w jej powstaniu polegał na opracowanie koncepcji artykułu, wskazaniu metodologii badań, zebraniu materiału badawczego, zebraniu literatury przedmiotu, przeprowadzeniu badań modelowych, analizie i interpretacji danych, wykonaniu obliczeń statystycznych, napisaniu i redakcji manuskryptu, przygotowaniu rycin, przygotowaniu odpowiedzi w procesie recenzji artykułu, co stanowi 70% całej pracy.

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Oświadczenie o współautorstwie

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....
podpis