Hydrology of small agricultural catchments in Norway, Latvia and Estonia

Av Johannes Deelstra, Hans Olav Eggestad, Arvo Iital,
Viesturs Jansons og Line J. Barkved

Johannes Deelstra and *Hans Olav Eggestad* are researchers at Bioforsk – Norwegian Institute for Agriculture and Environmental Research, Soil and Environment Division; Arvo Iital is associate professor at the Institute of Environmental Engineering, Tallinn Technical University, Estonia; *Viesturs Jansons* is professor at the Department of Environmental Engineering and Water Management, Latvia University of Agriculture, Jelgava; *Line J. Barkved* is researcher at the Section for Climate and Environmental modelling, Norwegian Institute for Water Research – NIVA.

Sammendrag

Denne artikkelen presenterer resultater av en evaluering av hydrologiens betydning for tap av næringsstoffer og jord i nedbørfelt i Norge, Estland og Latvia. Et viktig formål har vært å øke forståelsen av hydrologien i jordbruksdominerte nedbørfelter ved å se på forskjeller i karakteristikker mellom små og store felt, men også forskjeller i karakteristikker som oppstår når man analyserer på bakgrunn av gjennomsnittlige døgn- eller timeverdier for vannføringen. Kunnskap om hydrologien og hvordan den påvirker jord- og næringsstofftap er viktig for å kunne foreta riktige valg og gjennomføring av tiltak mot forurensning både nå og under fremtidige klimaendringer.

Avrenningen på sommerhalvåret er ubetydelig sammenliknet med de øvrige årstider. Særlige i de mindre felt viser det seg at nærmere 50 % av årsavrenningen, og tap av jord- og næringsstoffer, foregår i løpet av en periode kortere enn 1 måned, mens 90 % blir drenert bort på mindre enn 5 måneder. Også tidsoppløsningen har stor effekt på resultatene og førte til store forskjeller i beregnet spesifikk avrenning noe som tyder på at store døgnvariasjoner i avrenningen kan forekomme under visse forhold. En såkalt ”flashiness indeks” ble brukt for å beskrive variasjonen eller intensiteten i avrenningen. Det eksisterer store forskjeller i flashiness mellom feltene, men store forskjeller i flashiness oppstår også som en følge av tidsoppløsning. Analysen viser at den største flashiness finnes i mindre norske nedbørfelt, og at en viktig årsak kan være intensiteten, dvs. grøfteavstand, i norske grøftesystemer samt topografien.

Andre mulige årsaker som kan bidra til forskjeller i flashiness kan være nedbørfeltstørrelse og andel jordbruksareal, i tillegg til topografien.

Summary

This paper presents the results of an evaluation of the effects of hydrology on nutrient and soil loss in catchments located in Norway, Estonia and Latvia. The main objective has been to obtain an improved understanding of flow processes within agricultural catchments by comparing different hydrological characteristics. Some of the characteristics have been calculated based on both hourly and average daily discharge values. By taking into consideration different time resolutions improved insight into the dynamics of agricultural hydrology will be obtained. The understanding of hydrological processes at different scales and their effects on nutrient and soil loss generation is necessary to be able to effectively deal with climate change. Only then will we be able to implement the necessary mitigation measures to preserve water quality while at the same time maintaining a sustainable agricultural production.

The analysis showed that for all catchments, the runoff contribution is lowest during the summer season. Especially for smaller catchments 50 % of the yearly runoff is discharged in less than 1 month, which also seriously affects nutrient and soil loss, which are often even confined to a shorter period. For many of the smaller Norwegian catchments significant increases in specific discharge exist when using hourly – instead of daily time resolutions, indicating large diurnal variations in discharge. A flashiness index was used to describe the intensity or variation in discharge. Large differences in flashiness exist between catchment but also large differences in flashiness become apparent when using hourly time instead of daily time resolutions. The highest values for the flashiness index were obtained for the smaller Norwegian catchments, the main reasons for this probably being the subsurface drainage intensity and topography. Other possible reasons for differences in flashiness can be due to scale and the share of the agricultural land in the catchment.

Introduction

Agriculture contributes a significant portion of the nutrient losses to the environment, being to a large degree responsible for the eutrophication of inland waters and coastal zones. Agricultural practices, climatic conditions, topography and geological conditions are important factors in determining these losses. However, also hydrological flow processes and pathways play an important role in the nutrient and soil loss processes. This paper presents the results of an evaluation of the hydrology in 13 catchments located in Norway, Estonia and Latvia with the objective to obtain improved understanding of flow processes within agricultural catchments and their potential effects on nutrient and soil loss. All but two catchments can be characterised as small in size. These two were included to evaluate the effects of scale and proportion of agricultural land on the hydrological behaviour at catchments scale.

All catchments have been provided with equipment for continuous registration of discharge. Some of the characteristics have been calculated based on both hourly, as well as average daily discharge values. By taking into consideration these two time resolutions it is anticipated that improved insight into the dynamics of agricultural hydrology at different scales will be obtained. A prerequisite for effective agricultural production in Norway, Estonia and Latvia is the presence of an artificial subsurface drainage system. However, artificial drainage systems can have a significant influence on both hydrological flow paths and nutrient losses. Its magnitude is very much influenced by the soil type, drain spacing and depth (Skaggs *et al.* 1980 and Skaggs *et al.* 1994). Therefore, on four small catchments, only the subsurface drainage runoff behaviour has been analysed.

Knowledge about the dynamics of agricultural hydrology is important with respect to:

1. Their impact on nutrient and soil loss processes in agriculturally dominated catchments,
2. The choice and implementation of suitable mitigation measures to abate present and future pollution problems and
3. The design of hydro-technical implementations.

This knowledge becomes even more important when considering climate change, which in addition to an increase in the air temperature; predict an increase in precipitation mainly for the period after the growing season. This is already now the period when most of the nutrient and soil loss occurs.

Catchment description

All the Norwegian catchments, table 1, except Høgfoss and Lena are part of the Agricultural Environmental Monitoring Programme (JOVA). The Høgfoss catchment is part of the larger Vansjø – Hobøl catchment, while the Lena catchment is part of the Lake Mjøsa catchment. Also the Estonian and Latvian catchments are part of national monitoring programmes. The discharge is measured at the outlet of the catchments, using either a fixed discharge measurement structure or a calibrated rating curve. The main land use in the catchments is agriculture and forest, the rest being bogs and urban areas, ***Table 1***. There is considerable variation in the long term mean annual temperature and long term annual precipitation. The topography of the catchments varies from flat to hilly, with the largest differences in elevation in the Norwegian catchments. In all catchments most of the agricultural land is artificially drained. The Norwegian catchments are intensively drained, with a drain spacing varying from 8 – 10 m and a drain depth of 0.80 – 1 m. The drain spacing in the Baltic catchments varies from 20 – 24 m and a drain depth of 1 m below the soil surface.

Catchment		Size (ha)	Long term mean temp (°C)	Long term mean prec (mm)	Land use (%)
Høgfoss	Catchment runoff	29500	5.6	829	agr[1]. (19), for[2].(80), other[3](1)
Lena		18100	3.6	600	agr. (32), for.(55), other(23)
Hotran		2000	5.3	892	agr. (58), for.(30), other(22)
Mørdre		680	4.0	665	agr. (65), for. (28), other(7)
Skuterud		450	5.3	785	agr. (61), for. (29), other(10)
Kolstad		308	3.6	585	agr. (68), for.(26), other(6)
Räpu (Est.)		2550	5.5	742	agr. (77), for. (21), other(2)
Rägina (Est.)		2130	5.8	642	agr. (53), for. (47)
Mellupite c. Lat.)		964	6.1	633	agr. (68), for. (32)
Vandsemb	Subs. drainage	6.5	4.0	665	agr. (100)
Bye		4	3.6	585	agr. (100)
Vinningland		2.4	7.1	1189	agr. (100)
Mellupite d (Lat.)		12	6.1	633	agr. (100)

[1] – agriculture; [2] – forest; [3] – urban/housing area, peat soils

Table 1. Catchment characteristics

Vandsemb is located within the Mørdre catchment. Bye can be considered a nested catchment within Kolstad, although not located immediately within it. Also Mellupite drainage can be considered nested within the Mellupite catchment. Vinningland is a small subsurface drained field, located at Jæren in southwestern Norway.

Results

A number of hydrological characteristics have been calculated, table 2. Whenever possible these were calculated both based on hourly, as well as average daily discharge values. A summary of the results is presented in table 3, as average yearly values for the observation period.

Seasonality in runoff

Seasonality in runoff refers to the relative contribution of the different seasons in the total yearly runoff. In this case March – April represent the spring period, May – August the summer season, September – November the autumn season and December – February represent the winter season. For all catchments, the runoff contribution is lowest during the summer season, varying from 7 to 23% in

Parameter	Remarks
Seasonality in runoff	Runoff contribution in different seasons
Runoff generation	Days required for discharging a percentage of yearly runoff
Specific discharge	Discharge per unit area
Flashiness index	A measure of variation in discharge

Table 2. Parameters used in the characterisation of catchments

Mellupite catchment and Kolstad respectively table 3.

Lena and Kolstad have the highest runoff contribution during spring, this typically representing snowmelt generated runoff partly occurring during the month of May. They also have their lowest runoff contribution during the winter period confirming the influence of a more pronounced inland winter. For the remaining Norwegian catchments, the runoff generation is approximately equally distributed among the spring, autumn and winter period. Winter and spring runoff is dominating in the Estonian and Latvian catchments. Also, for the subsurface drained fields the lowest contribution is during the summer season. Compared to Vinningland, the runoff contribution during winter is considerably less at Vandsemb and Bye. The main reason for this is the more pronounced effect of winter on water transport through the soil due to below – zero soil temperatures.

Runoff generation

While seasonality showed that runoff mainly occurs during the off-season, run-

			seasonality				max. spec. disch. (l s^{-1} ha^{-1})		runoff days	FI		
Catchment		**runoff (mm)**	**winter**	**spring**	**summer**	**autumn**	**day**	**hr**	**50/90**	**day**	**hr**	**Period**
Høgfoss	Catchment	477	0.30	0.25	0.17	0.28	1.3	1.5	52/194	0.24	0.39	1988 - 2003
Lena		465	0.16	0.43	0.16	0.25	1.3	1.5	38/174	0.24	0.47	2001 - 2007
Hotran		767	0.35	0.29	0.13	0.23	4.9	8.5	28/145	0.60	1.82	1992 - 2005
Mørdre		282	0.23	0.35	0.16	0.26	1.7	2.8	24/138	0.54	1.56	1992 - 2005
Skuterud,		508	0.28	0.27	0.13	0.33	2.9	5.7	28/141	0.57	1.83	1994 - 2005
Kolstad		320	0.10	0.41	0.23	0.25	1.4	2.4	31/138	0.29	0.94	1991 - 2005
Räpu (Est.)		255	0.35	0.36	0.15	0.15	0.6	0.7	51/179	0.17	0.30	1997 - 2004
Rägina (Est.)		224	0.32	0.31	0.16	0.21	0.4	0.5	54/180	0.18	0.30	2000 - 2004
Mellupite c (Lat.)		252	0.49	0.24	0.07	0.21	1.0	1.2	29/140	0.37	0.67	1998 - 2002
Vandsemb	Subsurface	215	0.23	0.33	0.16	0.28	1.2	1.6	16/56	0.64	1.47	1992 - 2004
Bye		161	0.12	0.32	0.2	0.35	1.3	1.7	15/72	0.37	0.79	1992 - 2005
Vinningland		698	0.39	0.12	0.09	0.39	2.3	4.8	46/159	0.46	1.80	1998 - 2005
Mellupite d (Lat.)		241	0.45	0.22	0.07	0.25	1.3	1.6	25/120	0.51	1.10	1998 - 2001

Table 3. Hydrological characteristics

off generation actually is confined to only a limited period. Except for Høgfoss and Lena, it takes less than 1 month to discharge 50 % of the yearly runoff for the Norwegian catchments while less than 5 months are needed to discharge 90%, table 3. Scale might again play an important role when comparing Skuterud with Høgfoss, which have approximately the same amount of runoff, but differ considerably in the time to drain 50 – and 90 % of the yearly runoff.

On the other hand, compared to Hotran, it takes considerable longer to drain 50 and 90% of the yearly runoff in the Estonian catchments, although having the same size. The yearly runoff at Hotran is considerably larger and probably subsurface drainage intensity and topography are dominating in this case. Among the subsurface drained catchments, it takes longest to drain 50 and 90% at Vinningland, possibly caused by the considerably larger amount of yearly runoff. While having approximately the same runoff as Vandsemb, it takes longer to drain the runoff at Mellupite drainage, and in this case the less intensive subsurface drainage intensity might be the main reason. Although there are difficulties in determining what is the dominating effect on runoff generation, scale, topography and subsurface drainage intensity probably are the main reasons for the observed differences.

Specific discharge

The maximum specific discharge (l s^{-1} ha^{-1}) has been calculated on hourly – and average daily discharge values respectively. Based on average daily discharge values the specific discharge varies from 0.4 to 4.9 l s^{-1} ha^{-1} for the Rägina and Hotran catchment respectively while on hourly discharge values they vary from 0.5 to 8.5 l s^{-1} ha^{-1}, table 3. Especially for many of the smaller Norwegian catchments significant increases in maximum specific discharge occur when using hourly – instead of daily – time resolutions, indicating large diurnal variations in discharge.

Scale might be an important reason for explaining differences between catchments exemplified when comparing Skuterud with Høgfoss, having approximately the same yearly runoff. Also having similar yearly runoff, scale might be the main reason the difference between Mørdre and Mellupite catchment on the one hand and the Estonian catchments. Then again, Mørdre shows the largest increase in specific discharge when using the hourly time resolution, which is an indication of large diurnal variations in discharge due to differences in topography and subsurface drainage spacing. Among the Norwegian subsurface drained fields, Vinningland has the highest specific discharge, the main reason possibly being the total yearly runoff. The high specific discharge at Mellupite drainage field compared to the Mellupite catchment might be due to the larger size of the catchment and its land use with 30% occupied by forest.

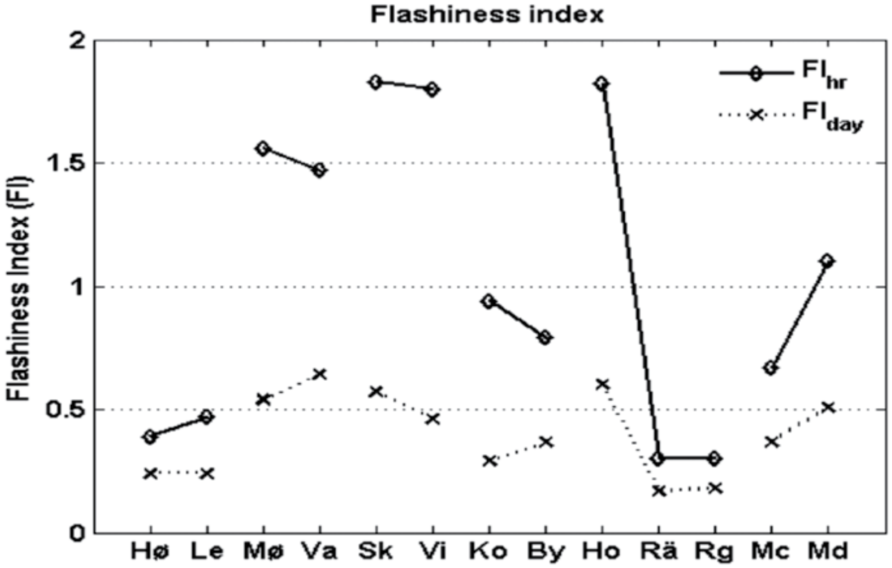
The flashiness index

Flashiness refers to how quickly flow changes from one condition to the other. Baker *et al* (2004) developed a flashiness index (FI) which was able to describe these changes and used it to detect changes in the hydrological regime of rivers. The FI is obtained by calculating the total sum of the differences in daily discharge divided by the sum of the average daily discharges as

$$FI_{day} = \frac{\sum_{i=1}^{n}(q_i - q_{i-1})}{\sum_{i=1}^{n} q_i}$$

where q_i and q_{i-1} are the average daily discharges ($m^3\ s^{-1}$) on day (i) and day (i-1), respectively. To take diurnal variations into consideration, the total sum of the differences in hourly discharge values is taken. Based on average daily discharge values, the FI varies from 0.17 – 0.60, the highest values for three of the smaller Norwegian catchments, indicating significant changes in daily discharge values, table 3. An increase in FI occurs when calculated on hourly discharge values, most pronounced in the smaller Norwegian catchments Mørdre, Skuterud, Hotran and Kolstad.

In many cases, more than one factor may be responsible for the difference in FI. Among the Norwegian catchments the larger Lena and Høgfoss have low FI values and although an increase in FI occurs when using a higher time resolu-



(Hø = Høgfoss; Le = Lena; Mø = Mørdre; Va = Vandsemb; Sk = Skuterud; Vi = Vinningland; Ko = Kolstad; By = Bye; Ho = Hotran; Rä = Räpu; Rg = Rägina; Mc = Mellupite catchment; Md = Mellupite drainage).

Figure 1. Flashiness index based on hourly and average daily discharge values

tion, the values are still considerably lower compared the smaller Mørdre, Skuterud, Kolstad and Hotran. The low FI might be attributed to the large size and the low share of agricultural land in Lena and Høgfoss. Mørdre, having approximately the same size as Mellupite, has a significantly higher FI value, which might be attributed to topography and subsurface drainage intensity. Hotran, of approximately the same size as the Estonian catchment, has a much higher FI values, also this possibly be attributed to topography and subsurface drainage intensity.

The role of subsurface runoff in the runoff generation at catchment scale is uncertain; however, some indications about its influence can be noticed. For example, being nested within the Mørdre catchment, Vandsemb subsurface drainage field has an FI being slightly less, which could be an indication of the relative large influence of subsurface runoff in the runoff at catchment scale. This is also the case when comparing the nested Bye subsurface drainage field with the Kolstad catchment. Although not nested within, Vinningland has almost the same FI as the Skuterud catchment. The FI for the Mellupite drainage field is higher compared to the Mellupite catchment due to scale and a larger share of forest in the main catchment.

Discussion and conclusions

Differences in hydrological characteristics like seasonality, specific discharge, runoff generation and flashiness index between catchments can be observed. The analysis showed that factors such as scale, topography, subsurface drainage intensity and the share of agricultural land in the catchment play a role in explain differences. However, there seems to be no straightforward answer to which factor is the most influential. The seasonality study showed that runoff is lowest during the growing season, May – August. On the other hand, there are significant differences in runoff generation depending on scale, topography and subsurface drainage intensity and these differences are important especially with regard to nutrient – and soil loss. For some of the catchments it takes less than 1 month to discharge 50% of the yearly runoff. The question arises how this affects the transport of nutrients and soil particles out of the catchment. An example is given for the Skuterud catchment for the years 1996 and 2007 showing that compared to runoff, it takes even less days to discharge 50 and 90% of the nutrients out of the catchment, especially for (P) and suspended solids (SS), table 4. Nutrient loss calculations at Skuterud are based on volume proportional composite water sampling which gives in general satisfactory results, often being recommended in load calculation from agricultural dominated catchments (Haraldsen og Stålnacke, 2005; Richards, 1998). The results obtained at Skuterud indicate that the choice of water sampling has to be able to take into consideration the N, P and SS dynamics when runoff generation is confined to a limited period during the year.

The results obtained for the specific

	Days				
year	%	runoff	N	P	SS
1996	50	17	14	10	7
	90	87	77	51	41
2007	50	26	23	16	12
	90	118	106	80	66

Table 4. Runoff, nutrient (N,P) and soil loss (SS) generation, Skuterud catchment, Norway

discharge lead one to conclude that considerable diurnal variations in discharge can occur, especially in the smaller Norwegian catchments. Diurnal variations in discharge were relatively small in the Baltic catchments exemplified by the small differences in specific discharge when calculated on hourly and average daily discharge values. Also in this case factors like scale, subsurface drainage intensity and topography can be considered the most likely reasons. An example of the influence of scale on specific discharge when using different time resolutions is given for Skuterud and Høgfoss, figure 2. A significant increase in maximum specific discharge occurs for Skuterud when based on hourly discharge values which is absent for Høgfoss and being an indication of the large diurnal variations in discharge within the Skuterud catchment.

Increased precipitation as a consequence of climate change will probably lead to more runoff, and for design of hydrotechnical implementations like culverts, bridges and drainage systems the maximum daily discharge values are very relevant to be taken into consideration especially when large diurnal variations exist. The analysis on the FI showed that it is not unlikely that subsurface drainage systems contribute considerably to the total runoff in the smaller Norwegian catchments. Subsurface drainage systems are necessary in Norwegian agriculture for a number of reasons one being that they control erosion induced by surface runoff induced erosion. Compared to Estonia and Latvia the Norwegian subsurface drainage systems have a very high intensity. Still uncertainty exists as to whether the present intensity of subsurface drainage systems is adequate in dealing with the increased precipitation due to climate change and thereby on maintaining its functionality with regard to controlling surface runoff induced erosion. Deelstra (2009a) claimed that the high precipitation during the autumn of 2000 in eastern Norway which lead to very high runoff, nutrient and soil loss could be an example of future climate change when high precipitation lead to.

The FI analysis showed that subsurface drainage systems might contribute significantly in the total runoff and that this can have implications for their contribution in nutrient losses and therefore also in the choice and selection of appropriate mitigation measures. Deelstra

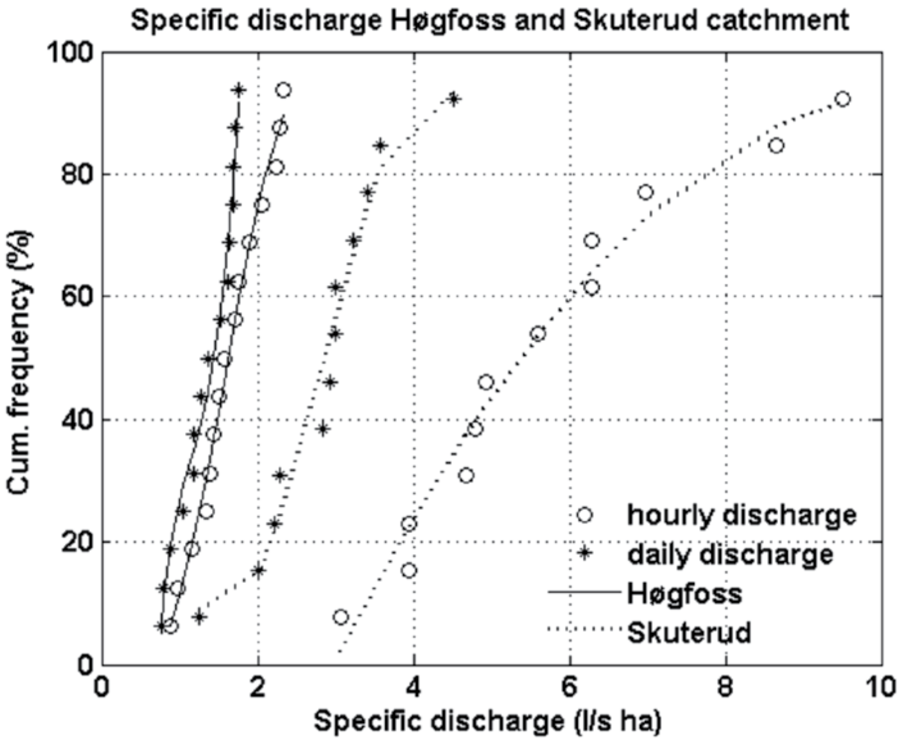


Figure 2. Specific discharge, Skuterud and Høgfoss catchment

(2009b) showed that indeed at the level of small fields like Bye and Vandsemb their contribution also was significant in nutrient loss. Kværnø and Bechmann (2010) confirmed this through an inventory on available measurements from small plot research, carried out in Norway by the Department of Plant and Environmental Science, University of Life Science and Bioforsk. If subsurface drainage really is contributing significantly in the total runoff at the Skuterud catchment, the question also arises as to what extent they contribute in particle transport. The dominating soils in the catchment are structured soils which can be characterised by preferential macropore flow and large areas in south eastern and central Norway have similar soil types.

The analysis has shown that significant differences in hydrological behaviour exist between catchments while at the same time significant diurnal variations in discharge can occur. Catchment scale, topography, the share of agricultural land and subsurface drainage intensity were indicated as possible causes for these differences. Especially the role of catchment scale and subsurface drainage systems has to be clarified as they play an important role in the nutrient transport and – retention processes. The observed "extremism" in hydrology, especially in smaller agricultural catchments, has to be taken into consideration to be able to evaluate the effects of climate change on catchment runoff generation, the diurnal variation in discharge and the implications this has for the design of hydrotechnical implementations and how this will affect the erosion and nutrient loss. The understanding of hydrological processes at different scales and their effects on nutrient and soil loss generation is necessary to be able to effectively deal with climate change. Only then will we be able to implement the necessary mitigation measures to preserve water quality while at the same time maintaining a sustainable agricultural production.

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