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Climate change and extreme weather conditions: Applications of geosynthetics securing flood defenses and coastal protection

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ABSTRACT: This article presents an overview of climate change research, predictions of global sea level rise, the increasing effects on coastal and riverine areas all over the world and furthermore an extensive overview of geosynthetic applications for flood defenses and coastal protection. Sea level rise, an important consequence of climate change, will lead undeniably to increasing problems concerning the safety against flooding and major challenges in design and construction of embankments. Where coastal and riverine areas are highly populated or have high economic value (business areas/industrial sites), flood protection schemes will require increasing efforts and capital investments. For climate adaption of flood defenses the application of geosynthetics can be of major importance. Building with geosynthetics is highly sustainable and enables the use of local less suitable soils. This results in reducing the use of primary granular building material, limiting transport distances and most importantly: decreasing substantial CO_2 emission. Other distinctive aspects are increasing construction speed, optimized building cost efficiency and reducing the amount of required space. Geosynthetics can be applied to ensure stability (embankments with reinforced soil and geogrids), top soil erosion control (3D structural mats, reinforced grass), coastal protection (sand-filled elements with bags, tubes or containers), controlling water level differences (drainage mats) or sealing levees (Geosynthetic Clay Liners - GCL). Implementing geosynthetics to meet one of these various functions to levees or coastal protection can give a considerable boost to the ambitions of global flood protection programs. For the big challenge to climate adaption geosynthetics will contribute to adapt safe and resilient living areas for humanity.

1 INTRODUCTION

The consequenses of global warming are evident and undeniable. More extreme weather conditions as well signs of sea level rise can be seen all around the world. The global sea levels have risen about 0.20 m during the last 100 years. However, the speed is increasing and research predicts 0.70 m sea level rise in 2100 with appr. 66% reliability [1]. Due to climate change also other hydraulic conditions are changing rapidly, with heavier rainfall conditions, more severe storm conditions, higher river discharges, increased flow velocities and wave overtopping. As billions of people are living in low laying areas near rivers and coastlines this will give major challenges to secure and improve flood defenses and flood

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protection schemes worldwide. Inevitable some living areas will be abandoned. All these threats influence already political decisions on transferring societies to more sustainable living. In the coming decades, huge improvement operations have to be initiated to keep as far as possible human living areas safe and resilient to climate change.

2 CLIMATE CHANGE IMPACT

2.1 *Sea level rise*

Sea level rise is one of the consequences of global warming. This relation is almost universally accepted today. The effect and consequences for people on earth are enormous. The IPCC (Intergovernmental Panel on Climate Change) has made global assessments of possible scenarios with predictions of sea level rise between 0.3 m and 1.5 m up to 2150 depending on the climate scenario [1]. A combination of measurements and predictions of sea level rise is given in Figure 1. A probabilistic study from 2017 indicates that with accelerated land ice loss in Antarctica the projected sea level rise could even increase to 1.8 m in 2100 (median value, scenario DP16, [4]). To compare, global sea level rise over the past 100 years was about 0.2 metres. Evaluations of measured sea levels between 1993 and 2018 in Australia show an increase of about 0.08 m over the last 25 years, already showing an accelerating trend (Australian Government Meteorological Office [5]). This presents clearly the major challenges in reinforcing or realising new flood defenses.

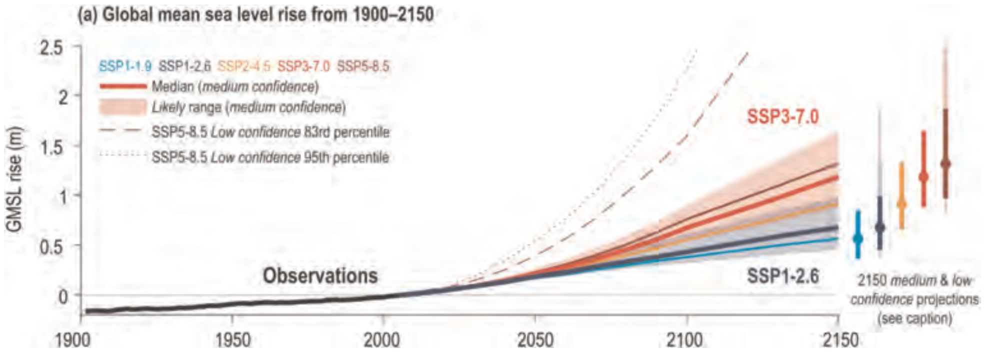

Figure 1. Projected global mean sea level rise under different SSP scenarios in timeframe 1950-2150 given in different colours and reliability range by IPCC (Box TS.4 Sea Level, [1]).

2.2 *Impact climate change*

The predictions of sea level rise obviously contain uncertainties, but even if values reach only half the predicted values, this already will have significant consequences for the safety, liveability and sustainability of residential, commercial and agricultural areas. Effects such as dune and beach erosion along coastlines as a result of high-water conditions will become increasingly frequent and intense (see Figure 2). The costs of maintaining coastlines will increase rapidly. Furthermore, sea level rise will lead to an increase in saline seepage. This salinization of groundwater will have considerable consequences for agricultural production in coastal areas. For the Netherlands the possible consequences of accelerated sea level rise have been charted [6]. Considerably more beach nourishment is to be expected, structural measures to maintain the fresh water supply and water safety, higher and wider flood defenses, and considerably higher frequencies in closing storm surge barriers like the Eastern Scheldt barrier in The Netherlands. In addition to increased sea levels, there are also other climate effects, like more extreme weather conditions having longer periods of intense drought or on the contrary more severe rainfall. Extreme discharges in the large European rivers such as the Meuse, Rhine, Donau and Volga will be higher and more frequent. The opposite is also possible: in 2018 large areas of Europe experienced a period of extreme drought with virtually no precipitation between the months of May and November [8]. In 2022 there was again exposure with sever droughts between April and August, resulting in extreme low river levels in large parts of Europe. Dehydration can have disastrous consequences to flood defenses. Extreme droughts affects deterioration and disappearance of peat layers and crack formation in impermeable clay layers [7]. The extreme droughts caused the major collapse of a peat levee near Wilnis NL in 2003 (Figure 3), resulting in flooding of the residential area behind and major capital damage.

Figure 2. Severe dune erosion after storm surge, Egmond aan Zee lighthouse, The Netherlands.

Figure 3. Arial picture peat levee collapse, caused by dehydration during extreme draught, 2003 Wilnis Netherlands.

2.3 *Impact damage or protection measures*

The global damage costs as a result of flooding's due to sea level rise are expected to increase enormously. A study published in 2018 [2] shows that at 0.86 cm sea level rise (RCP8.5 scenario, median value) and without additional measures for flood defenses, the worldwide estimated annual flood damage costs in the year 2100 are 11600 billion Euro/ year. If measures are taken to improve coastal protection, these annual damage costs could be reduced by about a factor 10. But the amount still remains enormous, indicating that the impact of sea level rise and consequential costs of flooding will be very high for all coastal areas worldwide.

By Deltares a study is done to look on the possible effects of accelerated sea level rises [6]. One effect is beach nourishment. The current situation involves the annual implementation of 12 million m^3 of sand on or in front of the beaches in The Netherlands to protect the existing coastline coasting appr. 42–60 million Euro. With a sea level rise of 15 mm/year there is a quantity needed 4 to 5 times as much, which could already be reached in 2050. In case of acceleration the amount and costs for maintaining the shoreline will be unprecedental. Another effect is the time period of protective measures. From the 90's safety measures could be taken with a functional lifetime of appr. 65 years. In case of acceleration this would be around 2060 reduced to a period of 20 years and upto the year 2100 even reduced to 10 years cycle. This would mean that steps for climate adaption will become increasingly difficult based on planning, efforts and financial costs. This results to an infeasible task living and fighting against rising water. Drastic measures and building methods to strengthen levees and coastlines will be needed.

Table 1. Amount of sand annually needed and related costs beach nourishment in The Netherlands [6].

Sea level rising speed (mm/year)	Required volume of sand (million m3/year)	Cost of beach nourishment (million Euros)
2	8	28–40 €
3	12 (current *)	42–60 €
5	20	70–100 €
12,5	50	175–250 €
30	120	420–600 €
40	160	560–800 €
60	240	840–1200 €

* current situation 12 million m^3 annual required sand for protecting the existing NL coastline.

3 GEOSYNTHETIC APPLICATIONS IN FLOOD DEFENSES

3.1 *Functions and applications to flood defenses*

For flood defenses, geosynthetics can contribute to many functions, like erosion protection, reinforcement, separation, sealing, drainage and filtration. The potential contribution using geosynthetics in levee reinforcements is considerable. For a long time, the construction of flood defenses has been focused on traditional methods using natural materials like sand, clay and stones [9]. However, increased safety requirements, preservation of landscape and buildings, rising sea levels and other climate effects continuously increase the complexity of levee reinforcements. Alternative and innovative techniques are increasingly seen as necessary and highly desirable, given the challenges for levee reinforcements in time. Also financial budgets for flood control will be more under pressure. Figure 4 shows a cross section of a flood defence construction, with multiple geosynthetics for various functions. These multiple geosynthetic applications in flood defences reduce the use of primary soil building materials, stimulate the use of locally available soil and reduce the environmental impact by a significant lower CO_2 emission.

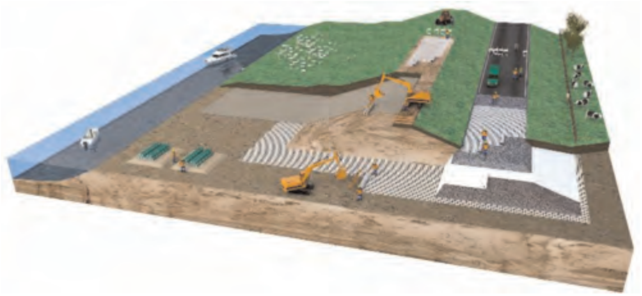

Figure 4. Systematic section of a high-performance flood defence construction with soil reinforcement, geosynthetic clay liner as a barrier, nonwoven geotextile for filtration and separation and erosion control products on the embankments.

To ensure flood security levels the speed and frequency of levee reinforcements will increase in the coming decades. Knowing this, it is very important that the design is made in such a way that the structure as easily as possible can be adapted during the next dyke reinforcement. In doing so, (geosynthetic) materials should also be easily removable from the ground again or structures which are extendable.

Embedding geosynthetics on larger scale into designs can result in a better, faster and/or cheaper construction of new flood defenses, levee reinforcements or coastal protections. This could give a considerable boost to the ambitions of global flood protection programs. Large-scale application with high performance geosynthetic building material in flood defenses has major potential. This paper illustrates the potential and added value of engineered materials to flood defenses to support the use of these alternative materials by designers, contractors and authorities.

3.2 *Geotextile filter constructions under stone revetments*

3.2.1 *Single nonwoven filter systems*

Construction of hydraulic filters can traditionally be done by using rock gradings in multiple layers according to filter rules concerning soil gradings, properties and hydraulic wave conditions. Doing so, traditional filtersystems can result in construction layers of 1–2.5 meter thickness. In lot's of countries rock is not widely available, and the rock must be transported over far distances. Single non-woven filter systems can be installed on the profiled subsoil and can fully replace the bottom filter layer. This can save between 0.3–1.0 m of granular filtermaterial. Beside these savings also CO2-emissions can be reduced with appr. 40–50% due to far lesser transport of materials. Due to the easiness of installation and cost efficiency. Geosynthetic filtersystems in rock revetments are widely used in hydraulic engineering projects. In Figure 5 an example is given of the construction of rock revetment, placed on a nonwoven filter. For the application it's very important to consider the filter rules and add adequate robustness to avoid damage by dropping stones (see paragraph 3.2.4).

Figure 5. Filter construction using a non-woven geotextile underneath a rock top layer.

Figure 6. Fascine mattress with geotextile filter layer and brushwood wickerwork as a filter construction underneath riprap.

3.2.2 *Fascine mattress applications*

A fascine mattress is a floating filter system which is prefabricated on land, towed onto the water to the construction site and submerged on location by controlled rock dumping. Initially, fascine mattresses were completely built up with natural materials, using willow branches and reed. Developments with geosynthetics made it possible to replace the reed and most of the willow branches by a geotextile since '70's. Willow branches are attached to the loops of the geotextile, making a square pattern (see Figure 6). This pattern stabilizes the fascine mattress for moving the fascine mattress into position. As towing and positioning by cranes can initiate large forces to the geotextile attention should be paid to the robustness of the materials used.

3.2.3 *Sand mattress applications*

A sand mattress is a geocomposite, existing of 2 layers of non-woven with a sand fill in between. By needle punching a firm heavy product is obtained for underwater installation. A sandmattress is delivered on rolls and can directly be installed from the slopes of banks into the water. Installation can be done by rolling out using a crane with a long reach, equipped with a hydraulic spreader bar (see Figure 7).

Figure 7. Installation of geocomposite sandmattress as filter layer below a stone revetment.

3.2.4 *Rock dumping impact on geotextiles*

Rock dumping on the geotextiles can cause serious damage. Various innovation and research programs are running to understand failure mechanisms of filter systems and improve design and application rules. Example is a CROW working group for geotextiles in rock revetments, active since 2019. This working group initiates field- and laboratory tests to understand the behaviour of geosynthetics with the energy impact by dropping stones. Multiple fieldtrial drop tests are done to analize the failure mechanism and dependency of the subsoil (clean loose sand, stiffer layering or intermixed with gravels). This is illustrated in Figures 8 and 9. Before the performance and failure mechanisms are also tested with laboratory research in Ghent [13,19].

Figure 8. Fieldtrial drop tests with selected stone classes on nonwoven geotextile and analysis of failure mechanism and test conditions subsoil.

Figure 9. Fieldtrial drop tests with selected stone classes on nonwoven geotextile and analysis of failure mechanism and test conditions subsoil.

Figure 10. Drop tests with standardized stone shapes and weight on composite geotextiles (woven/non-woven) at Ghent University.

These imply large scale droptests in laboratory conditions to single products and geocomposites (woven/nonwoven) with standardized stone shapes and weights (Figure 10). All data will be analyzed and embedded to an update of the NL design guide on geotextile filtersystems in rock revetments. See also Bezuijen [22].

3.3 *Water barriers with Geosynthetic Clay Liners (GCL)*

Traditionally, natural clay has been used to create artificial low permeable layers in flood defenses, both for the construction of the entire levee, sealing embankments or sealing the foreshore. In order to obtain adequate water retardation and erosion resistance, this clay must meet high requirements. Erosion-resistant clay is becoming increasingly scarce near project sites and often has to be transported from far away regions. This results in increasing construction costs and environmental impact. As an alternative to a thick layer of natural clay, it's possible to implement a Geosynthetic Clay Liner (GCL) to river levees. These mats with a thickness of approximately 1 cm, consist of multilayer high-quality geotextiles with bentonite powder in between. GCL's can be used to seal the foreland as an anti piping measure, or the levee itself. In addition to cost savings, the application of GCLs offers other major advantages to the use of clay: sustainability (energy requirement and CO_2 emissions for transport), construction speed (less deep excavation, no dewatering required), more use of near-site soil and less soil investigation required. Due to the swelling capacity of the bentonite, the mat is self-healing to a certain extent. Leakage through small holes (in the order of centimeters) for instance caused by mice or root growth will be stopped by swelling of the bentonite.

In Germany multiple projects with GCL's on flood defenses have been executed in the last decades, like along the Oder levee. The introduction of GCL's to in The Netherlands is done in 2 pilot projects initiated by Water Authority Limburg NL, being the levee reinforcement in Beesel and Neer. In Beesel the GCL is applied on the crest and slopes of the levee to replace a natural clay layer (see Figure 11). At the project in Neer the seepage length is extended by using GCL's to prevent piping (Figure 12).

Figure 11. Installation Geosynthetic Clay Liner (GCL) on a levee reinforcement to replace a 1 meter thick clay layer (Beesel Netherlands).

Figure 12. Horizontal installed Geosynthetic Clay Liner (GCL) in the levee foreland to enlarge the seepage length from the flood defense base.

3.4 *Geosynthetic Sand Containers (GSC's) for coastal protection and anti-scour*

One of the oldest applications of geotextiles in flood defenses is large geobag elements filled with sand. In 1957 these were already used to seal the Pluimpot, a small estuary near Tholen, The Netherlands. In the following years geotextile elements were further developed. Small elements like geobags can be filled on site and installed on beaches to stabilize the coastline

(Figure 13). Sand filled geotextile bags can also be used in deeper water to prevent scouring or to fill-up (big) scourholes. Scouring can occur in riverbeds by floods with extreme discharges, in harbours or by hydraulic turbulence to structures like dams and outlet structures. An example is the North Sea flood barrage in the river Eider (Germany), were major scouring was detected. After extensive research on the remedial measure to be taken, it was decided to fill the scourhole with 48.000 sandfilled geotextile bags to stabilize the underwater slope.

Geotextile elements are regularly used as breakwaters, dune foot defense structures, erosion protection or water retaining structures. These applications are used globally. The use of geotextile elements in coastal or flood defense structures could substantially reduce the risks and effects of beach and dune erosion. This may reduce the number of beach nourishments, cost and maintenance frequency of beaches and dunes after severe storms. Much literature is available on the application of geotextile sandfilled elements. A good overview of possibilities, research and calculations is given in several publications [16, 17 and 18].

In the area of Lubmin on the Baltic Sea, the existing coastline with sand dunes has been severely impacted by multiple storm surges. A solution is being implemented with a hidden underground protection using Geotextile Sand Containers (GSC). To reinforce approximately 2 kilometers of coastline, in total 34,000 sandfilled elements were installed. The elements weigh approximately 1.4 tonnes each and are used to construct the underground coastal defence structure below the beach surface. The bags are laid in two rows, inclined to the long side and stacked in an offset manner (see Figure 14). Being covered with sand, the structure is no disturbing factor in the landscape. Also important is that after implementating the hidden protection measure the beach area has no restrictions for tourism and beachlife.

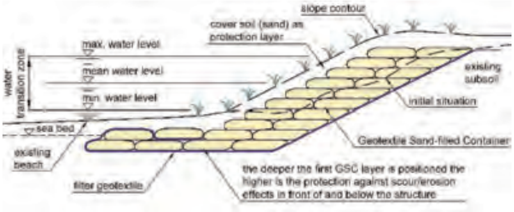

Figure 13. Schematic cross-section dune protection with Geotextile Sand Containers (GSC) underground structure, covering with beach sand and planting with helm grass.

Figure 14. Installation of Geotextile Sand Containers as coastal protection measure in the dune core of the sandy beach, Ludmin Germany.

3.5 *Erosion protection with 3D structure mats*

As a result of climate change there are higher waterlevels, currents, waves or heavy rain to be expected. Based on this more robust and intelligent erosion protection systems of flood defences will become increasingly important. Water levels will rise and the question is whether we can continue to build fully flood-resistant structures, or whether a certain degree of water spillover should be accepted. In the case of overflow levee structures, robust erosion protection is key.

Embankments can be protected against erosion in a natural way by a good (grass) vegetation with a clay under layer. This requires deep and good grass rooting of which the development takes in general at least two growing seasons. In The Netherlands it is mostly accepted that the turf has insufficient strength in the first months or even years, relying on the erosion resistance of the underlying clay layer. Also additional measures are taken at floods by installing so called cramming mats (geotextiles) over young turf to protect these from erosion. In other countries the requirements for initial strength of vegetated slopes at embankments are often higher. For example anchored three-dimensional geosynthetic structure mats are often used in America, but this application is also increasing to the European continent.

These 3D structure mats can be used to reinforce the top soil layer on embankments (see Figure 15). This mat provides protection of the bare soil or early vegetation, thus providing extra resistance to erosion. This prevents grass seed or young vegetation from being washed away, thus ensuring homogeneous germination. The effect of this is the development of a better-quality grass vegetation. In addition, the structure mat provides a permanent reinforcement of the top layer in the root zone. This may be necessary at locations where higher loads are expected, such as wave action, overtopping water and currents. In addition, the mat provides reinforcement in the case of a poor subsoil (grass on sand conditions) or where local damage can occur (animal burrows, sheep pathways, bicycle tracks, along stairs, structures, side's road pavements on the crest, etc.). During wave overtopping tests carried out on vegetated embankment slopes, it was observed that accelerated failure can occur in the event of local damage to the grass vegetation [20]. Extensive tests [21] were carried out to determine the erosion resistance including HPTRM (high performance turf reinforcement mats).

Figure 15. Installation of a reinforced High Performance Turf Reinforcement Mat (HPTRM) for slope protection.

In case of desirable rapid vegetation development, the choice can be made not to use grass seeds, but to apply hydro-mulching. In this process, a mixture of grass seed, nutrients and organic fibers is sprayed hydraulically into a 3D structure mat. For hydro-seeding or -mulching, attention must be paid to the quality of the seeds, nutrients and structure mat as all components have a major influence on obtaining a well-covered slope. Related to climate change seeds are to be chosen that are suitable for the changing climate conditions (more intense periodes wet and dry conditions). Research is also done to use different herb-mixtures, which stimulate also bio-diversity to levees.

Special attention should be paid to all types of transitions on slopes as often the loads are higher and the strength is less. In The Netherlands field tests on reinforced transitions are planned.

3.6 *Soil reinforcement for stability and steep slopes*

Raising embankments on soft soils can cause stability problems. A regularly applied solution is the installation of high strength soil reinforcement below the embankment. High strength reinforcement can be in the range of 300–1500 kN/m and can exist of woven-fabric, knitting or high-strength geogrids.

At the Oder levee along the German-Polish border a levee stretch with a length of 3 kilometres was reconstructed to withstand more extreme flood conditions. Soil investigations below the dyke stretch revealed relatively deep soft layers of peat, organic silt and clay. In order to ensure sufficient stability of the new dyke, a high strength geogrid of 1000 kN/m was installed as basal reinforcement (Figure 16).

Figure 16. Installation of high strength geogrids as basal reinforcement below the flood defence at the Oder dike, Germany.

Another application of geogrids to flood defenses is the realisation of steep slopes to reduce area use. Next to many flood defenses there are existing structures, like houses. In case of levee crest raising the footbase of the flood defence would be enlarged also. In case of space shortage, vertical constructive elements are designed to flood defenses, like sheet pile or concrete walls. When hard constructions like sheet piling are used in a levee, calculations show that these are heavily loaded, because this is a relatively stiff (settlement free) structure within the more flexible soil body.

As alternative steep slopes or even vertical retaining walls to flood defenses can be realized using geogrid reinforced soil structures. A description of implementation of geogrid reinforcement to flood defences is described in [11]. A comprehensive overview of possibilities, research and calculations is included in a publication on retaining structures of reinforced soil [15]. Retaining walls using geosynthetic reinforcement are generally flexible and are able to deform together with subsoil settlements. This makes geosynthetics ultimate suitable for levee reinforcements to soft soil areas. By using Finite Element Models (FEM) the effect between forces, deformation and interaction between soil and geosynthetics can be determined in detail. Due to the interaction, geosynthetics constructions behave as a block stabilization with considerable redistribution capacity. Another consideration is from research in Japan it is observed that reinforced soil structures behave very stable during earthquakes and big hydraulic impacts like tsunami's [14].

3.7 *Geosynthetic 3D composite drainage systems at levee structures*

As a result of higher water levels outside the levee and subsidence in the polders, the hydraulic loads on flood defenses will increase. The increase of the hydraulic head will have a negative effect on the stability of flood defenses. The hydraulic pressures can be positively influenced by using geosynthetic drainage systems, described in a publication of drainage techniques to levee structures [10]. Figure 17 shows the installation on a slope with a geocomposite drainage system and a Geosynthetic Clay Liner (GCL) on top. Levee drainage can be useful to avoid failure mechanisms such as macro and micro stability, but also piping. Examples of drainage are vertical wells, gravel boxes, horizontal drains or geosynthetic drainage mats. These drainage mats consist of geosynthetic 3D structure composites, which must be pressure-stable under the given conditions. These drainage mats can be installed vertically (for example as toe drainage), horizontally (partly under the embankment core or berm) or on the slope. This is illustrated in Figure 18.

Figure 17. Geosynthetic drainage composite mat (white color) with a Geosynthetic Clay Liner (GCL, light brown) on top as sealing system.

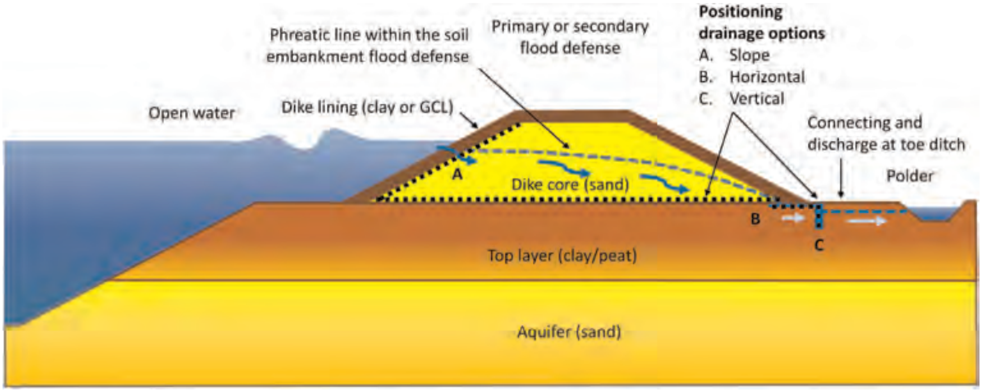

Figure 18. Schematic cross-section with freatic head in a river levee and options to decrease that phreatic head applying geosynthetic drainage systems, at slope (A), horizontal (B) and vertical (C).

4 CONCLUSIONS

Climate change will have significant effects on flood defenses globally. Aspects such as sea level rise and extreme weather conditions will have major consequences for the safety, quality of life and sustainability of residential, industrial and agricultural areas. In the coming decades huge and costly operations to flood defenses have to be initiated to keep local areas, larger regions or full countries safe and sustainable.

This article discusses the problems and effects of climate change and the potential positive role that geosynthetics can play in new or existing coastal and riverine flood defense systems: more sustainable, faster and/or cheaper construction. There are also major challenges in making (future-proof) designs with geosynthetics in embankments. Levees must be adaptable for subsequent levee reinforcements, in which case applied geosynthetics in the levee should not be an obstacle. When adapting future flood defences, geosynthetics should then be easily removable, re-usable or recyclable. In some application areas geosynthetics in flood defenses are still in an initial stage of development. Development of integrated concepts with geosynthetics offers a major potential to flood protection. Implementing geosynthetics to levees or coastal protection can give a considerable boost to global flood protection programs. For the big challenge to climate adaption geosynthetics can contribute to adapt safe and resilient living areas for humanity.

ACKNOWLEDGMENTS

To substantiate and illustrate this article figures are used. We would like to give full acknowledgements, with reference and copyrights to sources according Table 2.

Table 2. Reference and copyright to figures.

Reference and copyright	Figure number
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Rijk Gerritsen, Naue Prosé Geotechniek B.V.	8, 9, 18
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