Modeling bulrush growth along the Schelde

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Summary

The execution of the Sigmaplan can have a severe negative impact on ecologically valuable areas as marshbanks and mudflats along the Schelde. Therefore within the frame of the research project OMES an ecosystem model is developed to estimate the losses of valuable areas and to evaluate effects of alternative ways to carry out the Sigmaplan. This ecosystem model focuses on the role of macrophyte dominated intertidal areas in C and N fluxes through the estuary. An important question is: Do macrophytes like common reed and bulrush contribute significantly to the removal of ammonium from the system? The influence of macrophytes on the coupled nitrification-denitrification in the rhizosphere depends on the phenological development of the plant. Therefore growth models of reed and bulrush are needed. A bulrush growth model is developed within the scope of this research as a modification of a reed growth model (SUCREED). Most important modifications of the reed growth model are:

- Changing partitioning parameters because bulrush has no leaves;
- Implementation of a new method to calculate LAI (Leaf Area Index). LAI is a state variable in the reed growth model, in the bulrush model calculates the LAI based on the assumption of conical shaped stems;
- Changing the assumed spherical leaf-angle distribution of reed to a distribution using three leaf-angle classes for bulrush;
- The leaves of reed are assumed to reflect and transmit both 10% of the radiation. Due to the thickness of the stems (act as leaves) of bulrush the calculation of coefficients of reflection and extinction coefficients are based on stems that reflect 10% of radiation, transmittance is assumed to be zero;
- Incorporation of subroutine TIDE that accounts for temporarily floods due to tide on the Schelde.

The data used for calibration and validation were gathered during 1997 at a marsh bank near Appels (Belgium). The sensitivity analysis revealed that the model is sensitive for the EFF parameter (light use efficiency of individual leaves), but this parameter is known from literature. The model was found to be sensitive for parameters that determine the remobilization process and no accurate data could be found. Therefore these parameters were used to calibrate the model. The model performance after calibration is good, Goodness of Fit of 0.134. Validation of the model was done using a limited amount of data gathered during 1996 at the same marsh bank near Appels (Belgium) and showed an acceptable result (Goodness of Fit 0.619). It also revealed that the method used in the model to describe

phenological development of the plant is debatable. The method is based on summing daily temperatures from the calibration year (1997), because of temperature differences between 1997 and 1996 the phenological development is not accurately described.

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1 Introduction

1.1 Frame of the research

1.1.1 Sigmaplan and OMES

On 03/01/1976 large areas of Flanders (Belgium) were flooded as a result of a storm flood on the Schelde. This event resulted in drawing up the Sigmaplan, which contains measures to protect Flanders against floods in the future (Casteleyn & Kerstens, 1988). The security level maintained in the plan is equal as in the Dutch Deltaplan, and is based on a water level of 9.05 m TAW (Belgium Ordnance Datum; 2.33 m TAW equals to 0.00 m NAP (Dutch Ordnance Datum NAP)) in Antwerp. This water level has a statistical chance of occurring of once a 10,000 years, and can occur as a result of the combination of storm and spring tide. Due to industry and houses, it is not possible to raise the dikes everywhere along the Schelde, therefore the Sigmaplan consists of three parts:

1 raising dikes along approximately 500 km;
2 creating approximately 1100 ha of controlled inundation areas (cia);
3 constructing a movable weir, which can be closed during a storm flood.

The first part has been carried out for about 70%. About 500 ha of cia is already functioning, while about 600 ha of cia will be added in the coming years. Yet, no decision is taken concerning the third part, probably it will not be constructed in the near future (Meire *et al.*, 1997).

The Schelde estuary is a very important ecosystem, with on European scale very rare habitats like brackish and freshwater tidal mudflats and marshes (Meire *et al.*, 1995). One can imagine that further execution of the Sigmaplan can have a severe impact on this ecosystem. In AMIS (in Dutch: Algemene Milieu-Impactstudie voor het eerste deel van het Sigmaplan; study on the environmental impact of the Sigmaplan) several alternatives have been set up to compensate for the preliminary estimated losses of intertidal areas (Hoffmann & Meire, 1997). These are alternative ways to carry out the measures as described in the Sigmaplan. This was done in such a way that the safety aspect of the Sigmaplan was not negatively influenced.
In order to make a good estimation of the impact and influences of the alternatives proposed in AMIS, the Flemish government started a research project called OMES (in Dutch: Onderzoek Milieu Effecten van het eerste deel van het Sigmaplan;

research on the environmental consequences of the Sigmaplan). OMES is meant to provide a tool for integrated management of the Schelde estuary, so it would be possible to compare and judge effects of different alternatives. An ecosystem model of the Schelde should act as this tool, therefore OMES basically aims at building an ecosystem model of Schelde estuary which focuses on C and N fluxes through the estuary. The model should specifically focus on the role of intertidal areas and describe: (Meire *et al.*, 1997; Starink *et al.*, 1997).

- Catchment of organic and an-organic sediment;
- Transport of matter from the sediment to the water and fluxes of gasses to the atmosphere;
- Oxygen transport to the sediment. This process can initiate the microbial process denitrification;
- Production of organic matter.

Summarising can be stated that the Sigmaplan is a plan with measures to protect Flanders against floods as a result of a storm flood on the Schelde. Because of expected losses of ecologically important intertidal areas, several alternatives to execute the Sigmaplan are set up in AMIS. These alternatives aim at reducing the losses or even gaining ecologically important areas. To evaluate these alternatives the research project OMES was started in order to provide an ecosystem model of the Schelde estuary. This ecosystem model should act as a tool for integrated management, so different alternatives can be evaluated.

The way of functioning of a cia is explained in paragraph 1.1.2. More information on the structure of the ecosystem model and the position the bulrush growth model fulfils within this ecosystem model can be found in 1.1.3.

1.1.2 Controlled inundation areas

A controlled inundation area (cia) is a polder along the Schelde partly surrounded by a dike (so-called Sigma-dike) at the Sigmaplan security level (8.35 m TAW). Another, but lower (6.80 m TAW) dike (so-called inundation-dike) separates the polder from the Schelde. Under normal circumstances the inundation-dike acts as primarily dike, this means the polder is not flooded. In a situation of a storm tide the polder gets flooded and now the Sigma-dike acts as primarily dike.
Constructing 1100 ha of cia means a large expansion of storage capacity of the estuary, ensuring a higher security level for Flanders with relatively lower dikes. In order to drain the water from the polder to the Schelde after storm flood, weirs are

constructed through the inundation-dike (Biesemans, 1996). See figure 1.1 for a schematic representation of a cia.

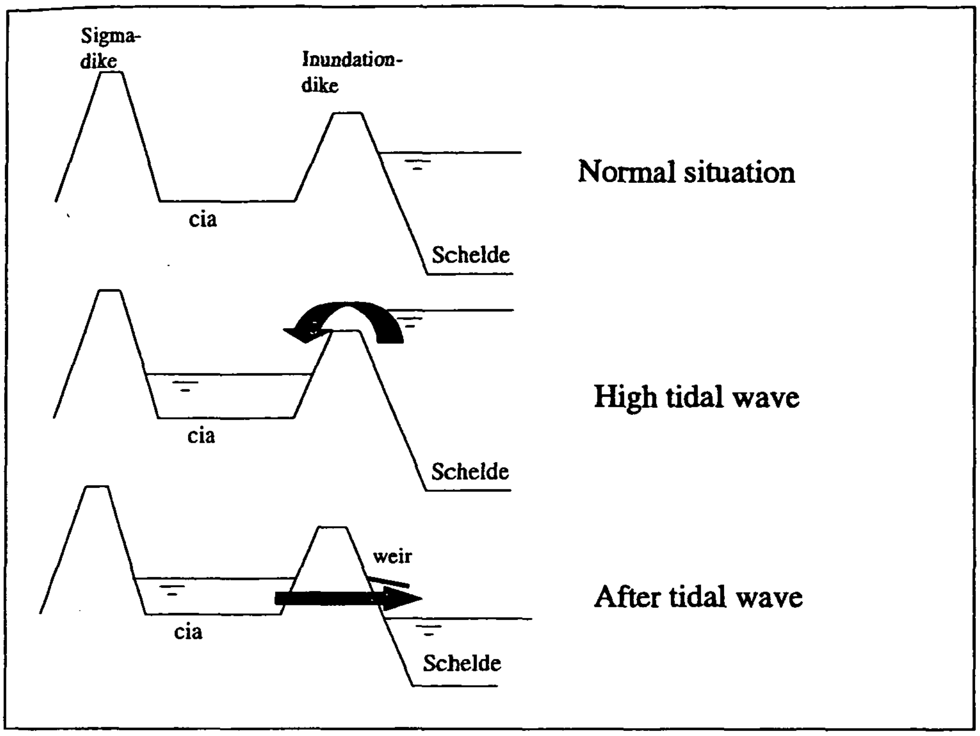

Figure 1.1: Schematic representation of a controlled inundation area

The estimated safety effect by the cia's is listed in table 1.1 (Biesemans, 1996).

	Water level at Antwerp (m TAW)	Statistical change of occurrence (y^{-1})
Without cia	7.58	25
With cia	8.25	400

Table 1.1: Safety effect of the controlled inundation areas

Originally the weirs through the inundation-dike were only meant to drain the water from the cia back to the river after a storm flood. There is however also an opportunity to use the weirs in normal situations, but now to flood the polder regularly. If the weirs are opened, they act as a pipeline that connects the cia through the inundation-dike directly to the river. Water from the Schelde flows into the cia or out of the cia, forced by the tidal rhythm. This ensures a changing water level in the cia, which allows growth of macrophytes like reed (*Phragmites australis*) and bulrush (*Schoenoplectus*). Because reed and bulrush are expected to influence benthic microbial processes (e.g. denitrification, see paragraph 2.3.2), this relation is an important issue in the ecosystem model.

1.1.3 The ecosystem model

The ecosystem model must evaluate effects of different alternatives and can therefore act as a tool for integrated management of the Schelde estuary (Meire *et al.* 1997). The model will be based on an existing model of the Schelde; MOSES (MOdel of the Schelde EcoSystem) (Soetaert & Herman, 1993), which will be spatially expanded and updated. It must consider the whole length of the Schelde influenced by tidal movement, from Vlissingen (Nl) up to Gent (Be). Also the cia's should be incorporated, especially the influence of reed and bulrush on benthic microbial processes. Literature research in Starink *et al.* (1997) reviewed that this influence depends on the phenological development of reed and bulrush. Therefore growth models of reed and bulrush will be coupled to a diagenetic model (Soetaert *et al.*, 1996) that describes benthic microbial processes. A growth model of reed (Mayus, 1996) was available, for bulrush such a model had to be developed. For a detailed scheme of the ecosystem model one is referred to Meire *et al.* (1997).

The diagenetic model describes benthic processes like denitrification, this process can be influenced by reed and bulrush. Therefore this influence is accounted for by linking growth models, which describe annual above- and belowground DW (dry weight) development, to the diagenetic model. Reed and bulrush effect the processes in the diagenetic model by taking up N and releasing oxygen and carbon from the roots to the sediment. This is schematically shown in figure 1.2.

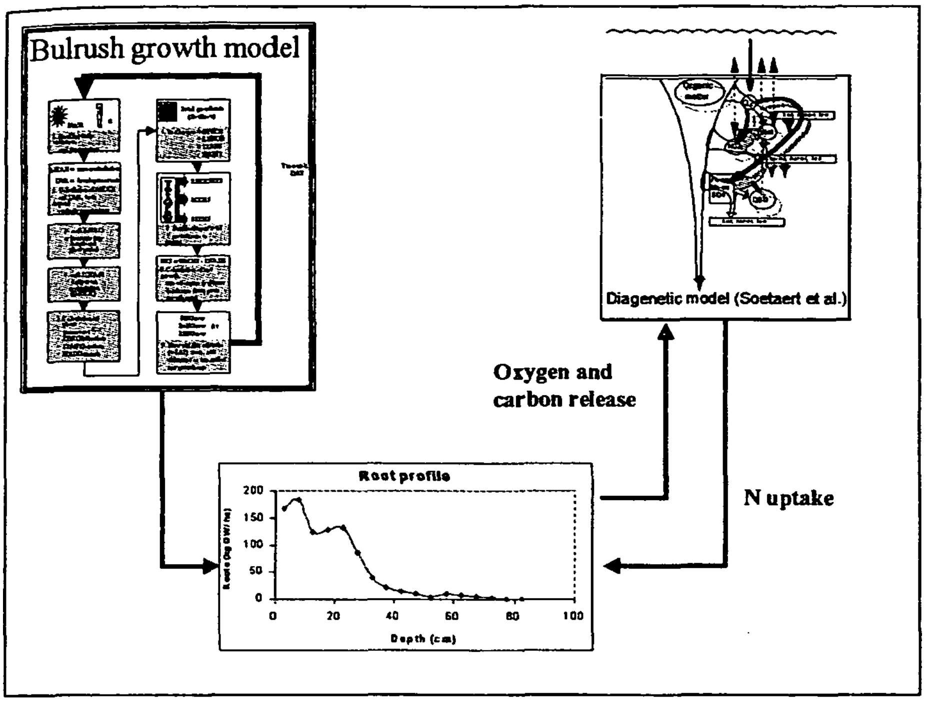

Figure 1.2: Coupling of bulrush growth model to diagenetic model

To gain more insight in the rhizosphere processes of reed and bulrush several laboratory experiments were conducted as well as field studies. Most of the fieldwork took place on the reed and bulrush vegetation at the freshwater marsh near Appels (Be). This study site at Appels provided also the data used for calibration and validation of this model, see appendix 4 for data.

1.2 Main research questions

The goal of this report is to adapt the growth model of reed (SUCREED) to a growth model that describes the annual above- and belowground DW (dry weight) development of bulrush along the Schelde, as a function of the meteorological circumstances, temperature and daily radiation.

The main questions to be answered are:

- How does the canopy of bulrush differ from reed, regarding adsorption and reflection of PAR and the leaf angle distribution?
- How can the modelled growth characteristics of reed be adapted to typical characteristics of bulrush, regarding organs, development rate and partitioning of organic matter?

The work was conducted, roughly following the next procedure:

I First the model **SUCREED** is studied in detail, to get a good understanding of the incorporated processes. **SUCREED** is incorporated in the simulation environment **SENECA** (de Hoop *et al.*, 1993) and the source code is written in **FORTRAN,** therefore **SENECA** and **FORTRAN** have to be studied.

II At the same time a literature research is started, to search for:

- Information on the ecology of bulrush;
- Morphological differences between reed and bulrush;
- Growth models of bulrush, or similar plants/crops;
- A theoretical background on light distribution in a canopy.

III The obtained information is used in order to adapt the growth model of reed to a growth model of bulrush, because of differences in canopy properties and plant organs

IV After the incorporation of the adaptations in the source code, the model is analysed. This is done by a sensitivity analysis (Monte-Carlo), which is a standard tool in **SENECA**. After the sensitivity analysis, several parameters are selected to calibrate the model. Calibration is also a standard tool in **SENECA.**

2 Ecology of bulrush

2.1 Taxonomy

Coops (1987) gives a review of the taxonomy of bulrush species found in Belgium and the Netherlands. These bulrush species belong to the genus *Scirpus* (Nl; mattenbies) which is one of the approximately 90 genera of the family *Cyperaceae*. The family *Cyperaceae* can be divided into three sub-families, namely *Scirpoideae*, *Rhynchosporoideae*, and *Caricoideae*. The genus *Scirpus* belongs to the sub-family *Scirpoideae*. The Dutch Flora (van der Meijden *et al.*, 1983) distinguishes 6 sections of the genus *Scirpus*, among these is *Schoenoplectus*. *Schoenoplectus* contains several species, from which *Schoenoplectus tabernaemontanus* (in Dutch; Ruwe Bies) is found at the study site at Appels (Be) (Hoffmann *et al.*, 1996).

So in this report 'bulrush' is defined as *Schoenoplectus tabernaemontani* or *Scirpus lacustris* spp. *tabernaemontani*, unless stated otherwise. Figure 2.1 is a drawing of *Scirpus lacustris* spp. *lacustris* (in Dutch: Mattenbies), a bulrush species that looks very similar to *Scirpus lacustris* spp. *tabernaemontani*.

2.2 Seasonal development

Bulrush is a perennial C_3-plant. Perennial plants live a specific annual cycle, which has several successive phases. During the winter months bulrush only has underground biomass, in the form of roots and rhizomes. The rhizomes contain reserve substances, mainly starch (Steinmann & Brändle, 1984), from which bulrush forms new shoots in early spring. Initially the new shoots grow mainly on reserve substances remobilised from the rhizomes. After several weeks the new shoots are large enough to grow on photosynthetic products. In spring and early summer these products are mainly used to build up the stems. Gradually more primarily production is used to refill the rhizomes with reserve substances, this process is called translocation. Flowering starts in July and lasts until medium August. After flowering the plant starts to senesce, in this period carbohydrates are transferred from the sloughing stems to the rhizomes to fill the rhizomes up with reserve substances. Gijzen (1985) found an allocation percentage of 29 % for cassave, so this process should not be discarded.

In September the senescing process is enhanced by eventual night-frost, resulting in fully senesced plants in the beginning of October. At this time the rhizomes are refilled with starch, to ensure that remobilization can take place in springtime. The dead plants initially lay on the sediment, but are gradually flushed away in December and January by tidal movement of the Schelde.

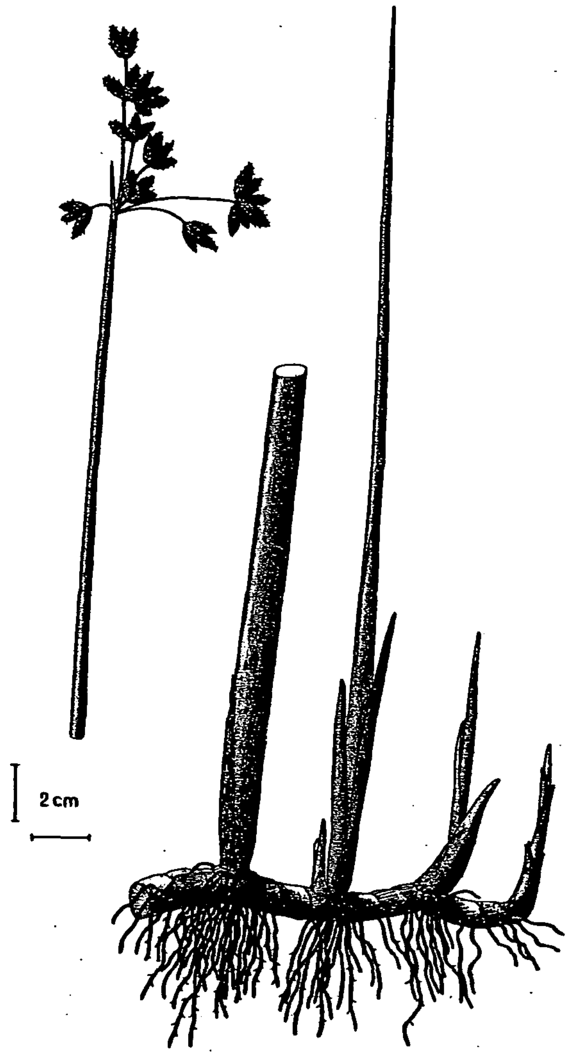

Figure 2.1: Drawing of bulrush (*Schoenoplectus* spp. *lacustris*)

2.3 Autoecology and ecophysiology

2.3.1 Sexual reproduction and vegetative propagation

It is known that bulrush has two ways of reproduction; sexual reproduction (van der Meijden *et al.*, 1989) and vegetative propagation (Ondok, 1972). Both ways are important, though vegetative propagation is most important within propagation of an

established bulrush stand (Coops, 1987). Sexual reproduction is most important in long-distance dispersal and dispersal to hydraulic isolated areas.
Vegetative propagation takes place through growing of rhizomes, from which new shoots emerge in springtime (Ondok, 1972).
Sexual reproduction takes place by wind induced pollination. Besides air and waterfowls, water is the main way for seed dispersal. A Ft_{90} (floating time of 90% of seeds) of 1.1 hour was found for seeds of *Schoenoplectus lacustris* and are therefore qualified as short-floaters. Short-floating seeds are expected to end up in lower elevations of the shoreline, this is also were the seeds preferably emerge (Coops & van der Velde, 1995).

2.3.2 Physiological adaptations to the environment

Generally *Schoenoplectus* species are found at deeper parts of shorelines of fresh or brackish waters, e.g. the Oude Maas (Coops & Smit, 1994), the IJsselmeer region (Coops, 1996) and the Schelde (Meire *et al.*, 1995). These habitats are dynamic, e.g. by tidal movement and salinity changes, and the sediments in which bulrush grows are anoxic. Therefore bulrush has several properties to survive this harsh environment. A short review of some of these properties is given below.

Established bulrush can grow in permanent or temporarily flooded sediments (Squires & van der Valk, 1992; Coops, 1996), this was also found for *Schoenoplectus lacustris* (van den Brink *et al.*, 1995). Nevertheless, water levels were found to be a strong selective force during seedling establishment, and may explain the zonation of *Scirpus* along a gradient in water depth (Clevering *et al.*, 1996). In Weisner *et al.* (1993) water levels were considered as the main force for occurrence of *Schoenoplectus* in large areas instead of *Phragmites australis*. The rhizomes of *Schoenoplectus* are equipped to withstand periods of anaerobiosis, which occurs during the winter months when the stems are dead and no oxygen is transported to the roots and rhizomes (Barclay & Crawford, 1982; Monk *et al.*, 1984).
Coops *et al.* (1994) concluded that wave exposure has only a negative effect on the biomass production of *Schoenoplectus lacustris* in deeper water and, once established, expansion to deeper water probably occurs through vegetative propagation.

The sediments in which bulrush grows are anoxic. This has two main negative consequences:

- no oxygen is present for roots and rhizomes to act as electron acceptor;

- a low redox potential in the sediment, which causes the presence of toxic compounds like sulphides, and several iron and manganese compounds (Tessenow & Baines, 1978).

To neutralise these factors stems of bulrush have aerenchyma, a special tissue to transport oxygen to underground organs. In wetland plants this transport can be an advective or diffusive process (Dacey, 1980), in *S. lacustris* this transport process is mainly diffusive. Haldemann & Brändle (1982) showed that this diffusive oxygen transport is very efficient. This transport ensures the availability of oxygen in the underground organs and the rhizosphere is oxidised through oxygen release from the roots to the sediment. Due to this oxygen release no negative influence of toxic compounds occurs (Armstrong, 1967; Haldemann & Brändle, 1982).
The released oxygen can also initiate nitrification by bacteria (Reddy *et al.*, 1989). If the formed nitrate diffuses to anaerobic parts of the sediment, bacteria can use this nitrate as electron acceptor in the denitrification process. This means that ammonium is transformed to nitrogen, which leaves the system. See figure 2.2 for a schematic representation. So it is expected that macrophytes with aerenchyma anchored in anaerobic soils can contribute to removal of nitrogen from the system (Christensen & Sørensen, 1986).

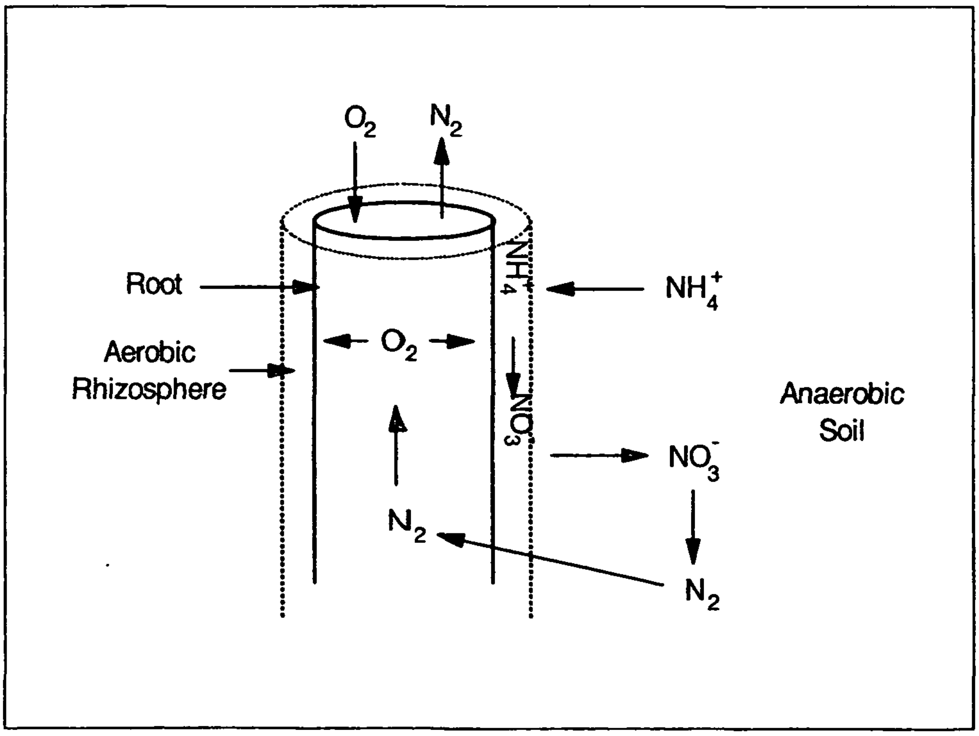

Figure 2.2: Denitrification in the rhizosphere of bulrush (Reddy *et al.*, 1989)

3 Bulrush growth model (BGMOD)

3.1 Theoretical background

SUCROS (Simple and Universal CROp Simulator) is a simulation model to simulate crop production (Goudriaan & van Laar, 1994).

The reed growth model SUCREED (Mayus, 1990) is a modification of SUCROS, main modifications are incorporation of the specific perennial plant processes; remobilization and translocation. SUCREED is incorporated in the simulation environment SENECA (de Hoop *et al.*, 1993), this gives the user the opportunity to use tools as sensitivity analysis, calibration, uncertainty analysis and parameter estimation (de Hoop *et al.*, 1993). Also calculation time, specific integration properties can be adjusted, and graphs or tables can be made. The source code of SUCREED is written in FORTRAN. The bulrush growth model (BGMOD) is based on SUCREED, but several modifications were implemented:

- In SUCREED a spherical leaf area distribution (no preferred orientation of leaves) and equal transmission and reflection of radiation (10% each) of individual leaves was assumed. Because canopy properties of bulrush differ clearly with reed, these assumptions do not hold for bulrush. Therefore a three class leaf-angle distribution was used in BGMOD. The transmission of individual leaves was assumed to be zero, reflection was assumed to be 10%. The new assumptions resulted in a different calculation of the reflection and extinction coefficients, these are needed to calculate the amount of absorbed radiation.
- In SUCREED plant organs consisted of underground organs, stems and leaves. Bulrush has no leaves and this organ is therefore removed. Important within the coupling of the bulrush growth model to the diagenetic model is that the model distinguishes roots and rhizomes, because roots release oxygen and take up nitrogen. So bulrush is consists in this model as roots, rhizomes and stems.
- LAI is incorporated in SUCREED as a state variable. The LAI in BGMOD is calculated as the surface of stems that are assumed to be conical shaped. The DW of a stem determines its length and thickness, using empirical relations between DW and length/ thickness. The length and thickness are used to calculate surface of a stem.
- Implementation of a new subroutine called TIDE. This subroutine calculates the amount of LAI that is flooded because of tidal movement of the Schelde and is therefore not available for assimilation.

3.2 Main assumptions

Development stage

SUCROS describes the phenological development of a plant by a dimensionless development stage (DVS). These stages can be arbitrarily chosen, but commonly stages like emergence and flowering are chosen. For bulrush the phenological stages used in the model are listed in table 3.1, more information can be found in appendix 3.

Description	Day number	DVS
Winter phase	0	0
Emergence	87	0.17
Flowering	212	1
Start senesce	243	2
Fully senesced	273	3
Post growth phase	365	4

Table 3.1: Summary of the development stages (DVS) used in BGMOD

The DVS is the integral of the development rate (DVR) (1/ d), the daily DVR increases linearly with the daily average temperature. As it is impossible to measure the DVR directly, it has to be calculated based on temperature sum between stages (see appendix 3). DVS is an important feature in the model because following functions are related to DVS:

1. Partitioning of dry matter to stems (+ flowers), roots and rhizomes;
2. Start of remobilization;
3. Death rates;

The relation between these functions and DVS is established using so-called DATA-tables defined at the beginning of the model, e.g. the DATA-table StFracTable;

DVS	Fraction to stems
0	0.90
0.48	0.90
0.59	0.7637
0.79	0.8451
1.42	0.9411
2.04	0.9194
3.45	0
3.999	0

From this table it becomes clear that the DVS determines the fraction of the total growth (kg DM/ ha/ d) partitioned to stems. For intermediate DVS values, linear interpolation is used to find the accompanying partitioning value.

Assumptions regarding processes

As described in chapter 2 bulrush has several specific properties. Some of them are important to incorporate in this growth model, others can be neglected considering the goal of the model. Also some important processes will be implemented when BGMOD is linked to the diagenetic model (see figure 1.2). The processes that are incorporated and neglected in BGMOD and important assumptions that were done are summarised.

Incorporated processes

- Remobilization is the main process that causes new shoots to emerge in spring.
- Translocation, is the process that refills rhizomes with reserve substances.
- Inundation, the tidal movement on the Schelde results in temporarily flooding of the bulrush stand (partly or complete) which inhibits assimilation. For submerged leaves of *Phragmites australis* a very low assimilation rate was found (Sand-Jensen, Pedersen & Nielsen, 1992), therefore assimilation of submerged stems is assumed to be zero. The tide on the Schelde is approached using a sinusoidal model. Within the ecosystem model so far no hydraulic part is available, therefore or this moment the sine approach of the tide is acceptable.

Neglected processes

- Propagation, the model describes annual DW development of an established bulrush stand. No propagation, vegetative or sexual, was included in the model.
- Water stress, because sediments along the Schelde have a high water table, no water stress is expected.
- Nutrient stress, the Schelde and the sediments along the Schelde have high nutrient levels, therefore no growth limitation by nutrient stress was expected.
- Nutrient uptake, this important process will be added when BGMOD is actually linked to the diagenetic model. This process is important because it influences benthic microbial processes.
- Organic carbon release from roots to the sediment influences microbial processes, this process is implemented when BGMOD is linked to the diagenetic model.

- Sidelight, because bulrush grows as strands along shorelines, sidelight contributes to the absorbed radiation in the stand. Within the present model this is not taken into account, the radiation profile is calculated assuming an infinite canopy surface. There are modules available that account for sidelight, these can be implemented in BGMOD.

3.3 Schematic representation of the model

This paragraph gives a structured overview of the model with a schematic representation (figure 3.1) and an accompanying elucidation. For detailed information on the model one is referred to paragraph 3.4.

3.2.1 Initialisation

In the initialisation part DATA-tables are defined which are used in the dynamic part and initial values of state variables (stems, roots, rhizomes, DVS) are set. Also diffuse radiation related parameters are calculated these are used in subroutine ASSIM.

3.2.2 Dynamic

The dynamic part consists of the next steps:

D 1) Reading of daily total radiation and maximum and minimum temperature from meteorological measurements.

D 2) Calculation of temperature depending variables AMAX (maximum CO_2 assimilation rate) and DVR (development rate). AMAX is a variable used in a photosynthetic-light curve used in ASSIM to calculate local assimilation rates. DVR is integrated every day to calculate a new DVS (development state) at the end of a day.

D 3) Call to subroutine ASTRO, to calculate photoperiodic and astronomic day length, as well as parameters like solar constant (SC) and daily total sine of solar elevation (DSINB).

D 4) Call to subroutine TOTASS. TOTASS uses parameters calculated by ASTRO to determine:

- Direct (PARDIR) and diffuse (PARDIF) amount of PAR (Photosynthetic Active Radiation) of the total daily radiation;
- Sine of solar elevation.

Subroutine TIDE is called, to calculate the water level of the Schelde and the submerged LAI, which is not available for assimilation.

Then ASSIM is called, this subroutine performs an integration of assimilation rates at different levels through the canopy, to determine canopy assimilation rate; FGROS (kg CO_2/ ha/ h). Assimilation rate is calculated with a photosynthetic-light response curve of individual leaves. ASSIM and TIDE are called five times a day and integrated by TOTASS to a total daily assimilation rate; DTGA (kg CO_2/ ha/ d). DTGA is transferred to GPHOT (kg CH_2O/ ha/ d) by multiplying with the molecular ratio of 30/ 44.

D 5) Calculation of the processes remobilization (kg DM/ ha/ d), translocation (kg CH_2O/ ha/ d) and maintenance (kg CH_2O/ ha/ d).

D 6) The total growth rate (TotGrow) can be calculated as:

TotGrow = (GPHOT + Trans – Maint) / ASRQ + Remob

The TotGrow is transferred to (kg DM/ ha/ d) by deviation with ASRQ (assimilate requirements to transfer CH_2O to DM (kg DM/ kg CH_2O)). Remob is left out of the deviation because this process is already expressed in kg DM/ ha/ d.

D 7) The TotGrow is partitioned among the stems, roots, and rhizomes depending on the DVS of the plant (by DATA-tables defined in the initialisation part). Now a gross growth rate of organs is known.

D 8) The net growth rate of organs is calculated by subtracting death rate (depending on DVS) from gross growth rate.

D 9) The new weight of plant organs is calculated as the integral of net growth rates. The new DW of stems is used to calculate LAI. Based on relations between DW (dry weight) and thickness of a stem and DW and height of a stem, the surface (conical shape assumed) of a stem can be calculated. The calculated surface of one plant is multiplied with the number of plants per square meter (NPL) to determine total surface of bulrush per square meter. The LAI (m^2/ m^2) is calculated as total surface per square meter multiplied with 0.5. Multiplying with 0.5 is necessary like for horizontal leaves the LAI is only the top surface of a leaf. The LAI is used by ASSIM the next day to calculate canopy assimilation.

3.2.3 Subroutines

A description of subroutines ASTRO, TOTASS, TIDE, and ASSIM can be found in figure 3.1.

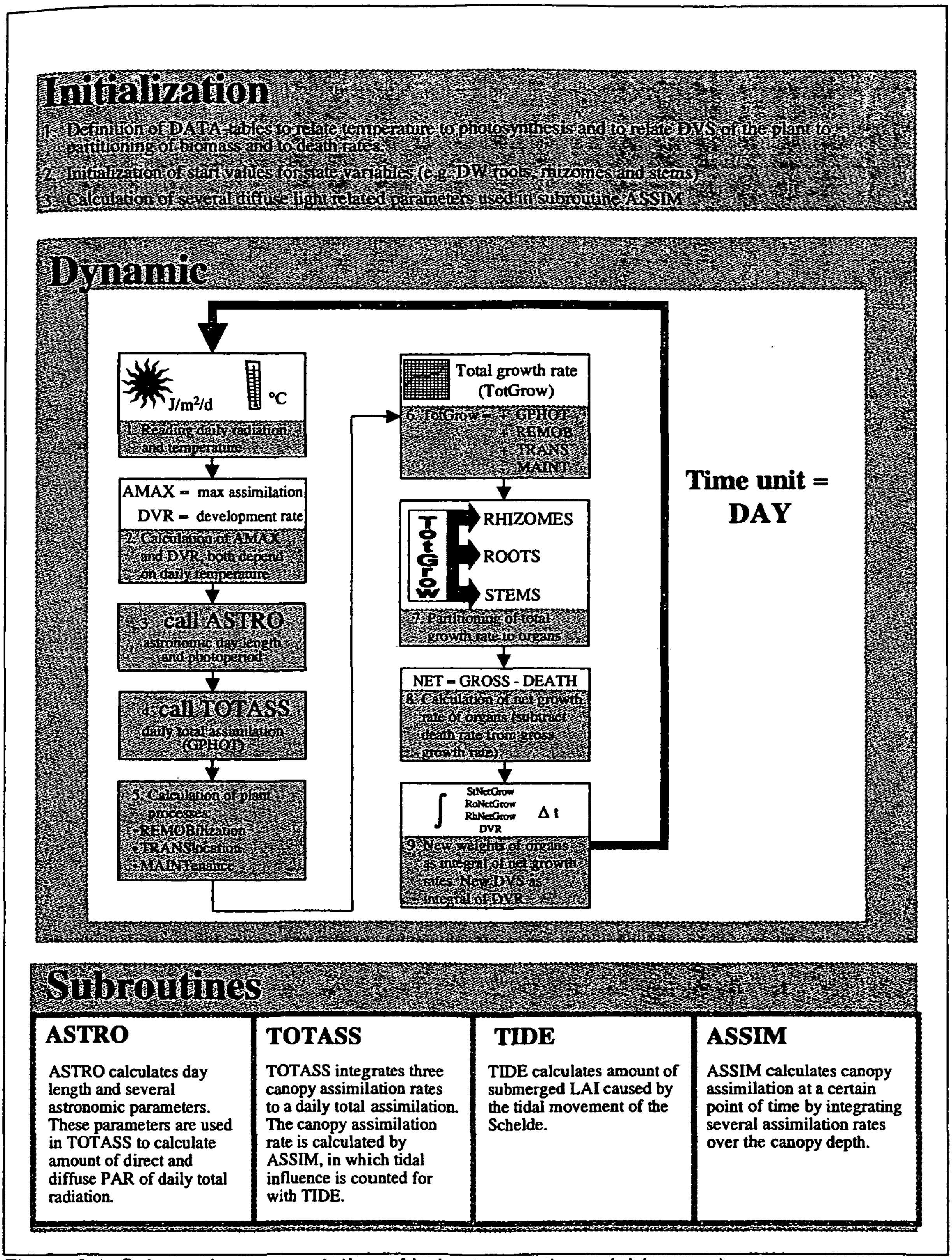

Figure 3.1: Schematic representation of bulrush growth model (BGMOD)

3.4 Detailed description of the model

In this paragraph the initialisation part, the dynamic part, and the subroutines are described in detail. For the initialisation part headers like I 1) are used and for the dynamic part D 1). Description of subroutines is headed by the name of the subroutine. Sometimes source code is used to clarify the model. In the source code several parameters, variables and state variable are followed by (I), e.g. StLive(I). This refers to the compartment number, this means that different study sited can be modelled. In BGMOD only one compartment was distinguished, but in the future the model can be expanded to more compartments.

I 1) Definition of DATA-tables

As described in paragraph 3.1 DATA-tables are used in BGMOD to relate temperature or DVS, to several variables (e.g. partitioning of dry matter production among the organs). The meaning of different DATA-tables is discussed below, the tables can be found in appendix 1.

AMTMPT:

This table holds the temperature effect on maximum assimilation rate. More information on this DATA-table can be found in D 2).

DVR0to1, DVR1to2, DVR2to3, DVR3to4:

The model distinguishes four DVS for bulrush, the DVS of the plant determines which DATA-table is used to calculate the DVR on a specific day. DVR1to2 contains the DVR of bulrush between the DVS 1 and 2. For example when the DVS equals 1.3, the model chooses the DATA-table DVR1to2. This table is used to calculate the DVR on a specific day depending on the daily average temperature (DAVTMP). Information on how these tables are established can be found in appendix 3.

StFracTable, RoFracTable, RhFractable:

These tables hold the fraction of the total growth partitioned to the plant organs, depending on the DVS of the plant. Information on how these tables are calculated can be found in appendix 5.

StDeathRateTable, RoDeathRateTable, RhDeathRateTable:

These DATA-tables hold the relative death rate of each organ used in the model. Because no field data were available, the death rates as set in the RoDeathRateTable and RhDeathRateTable were found by calibration of the DW development of roots and rhizomes. This calibration was done by running the model with different RoDeathRateTables and RhDeathRateTables. The RoDeathRateTable and RhDeathRateTable that gave an acceptable model performance were set in the model. As can be found in appendix 4 the standard error of the data of the underground is high. Therefore it was accepted that the model approximated the measured data on DW development of roots and rhizomes. No further efforts were done to improve the results of the model regarding the roots and rhizomes.

Due to a lack of data on relative death rate of the stems, it was not possible to calculate the StDeathRateTable. The death rates of stems were assumed to be zero until DVS 3, at this DVS the stems of bulrush are fully senesced. Therefore the death rate at DVS 3 was set to a high value, ensuring complete senesced stems at DVS 3.

I 2) Setting start values of state variables

When variable 'TIME' equals zero, the state variables are set to there initial values, these are defined in SENECA. All the initial weights of dead material are zero, as well as the initial weight of the living stems (therefore initial LAI equals zero). The initial weight of the roots and rhizomes is set to the weight found in samples taken on 12/06/1996 (appendix 4). Although these values are obtained in 1996 they are used in the simulation run for 1997, because data on underground DW (dry weights) are lacking in 1997. Besides this, the standard error on the data from 1996 is high (appendix 4), therefore these data should be looked at as an estimation of DW of roots and rhizomes. Because no major differences between DW of roots and rhizomes in 1996 and 1997 are expected, the DW values of 1996 are thought to be acceptable to use in 1997.

The variable RhRemob (kg DM/ ha) is the pool from which DM is remobilized in springtime. This pool is set at the beginning of the simulation as a vast amount of the DW of living rhizomes.

I 3) Diffuse radiation related parameters

Calculation of following parameters is needed because these are used in subroutine ASSIM to calculate absorbed radiation. This calculation needs reflection and extinction coefficients for diffuse and direct radiation. More information on the function of these parameters can be found in 'Subroutine ASSIM'.

```
C *---Reflection coefficient for horizontal leaves (RefH), K15, K45,
      K75
      RefH = (1 - SQRT(1 - RHO**2))/RHO
      K15 = SQRT(1 - RHO**2)*(1.00*F1 + 1.82*F2 + 2.26*F3)
      K45 = SQRT(1 - RHO**2)*(0.93*F1 + 0.68*F2 + 0.67*F3)
      K75 = SQRT(1 - RHO**2)*(0.93*F3 + 0.65*F2 + 0.29*F3)
```

The reflection coefficient for horizontal leaves (RefH) depends only on the reflection coefficient of individual leaves (RHO), it is used in the calculation of the reflection coefficient for diffuse (RefDif) and direct (RefDir) radiation.
K15, K45, and K75 are coefficients used in ASSIM to calculate the extinction coefficient for diffuse light (KDif), based on Goudriaan (1994; 1988). These coefficients only depend on leaf-angle distribution and reflection coefficient.

```
C *---Reflection coefficient for diffuse radiation (RefDif)
     DATA Y/15,45,75/
     DATA W/0.178,0.514,0.308/
      RefDif = 0.
     DO 5 X = 1, 3
      D1 = AMAX1(0.26, 0.93*SIND(Y(X)))
      D2 = AMAX1(0.47, 0.68*SIND(Y(X)))
      D3 = 1 - 0.268*D1 - 0.732*D2
      D = F1*D1 + F2*D2 + F3*D3
      RefDif = RefDif + W(X) *(RefH * 2. * D) / (D + SIND(Y(X)))
5    CONTINUE
     END IF
```

Reflection coefficient of diffuse radiation (RefDif) is calculated as a weighted average of the reflection coefficients of direct radiation with a sine of solar elevation of 15°, 45°, and 75°. This is done because all directions of radiation are present in diffuse radiation. Weight factors are based on a standard overcast sky (Grace, 1971).

D 1) Daily radiation and temperature

In D1 total radiation and temperature values are read from a file containing measured data. Temperature data are recorded at Zele (Belgium) and daily total radiation data are recorded at Munte (Belgium), these stations of KMI (in Dutch: Koninklijk Meteorologisch Instituut van België; Royal Meteorological Institute of Belgium) are closest to Appels. The daily average temperature (DAVTMP) is used in D2 and D5, daily temperature (DDTMP) in D2, and effective temperature (DTEFF) in

D5. More information on the calculation of different temperatures can be found in Goudriaan & van Laar (1994).

D 2) Maximum assimilation and development rate

Due to a lack of information on assimilation parameters for bulrush, the procedure and data (described below) from SUCREED are used in BGMOD.
In subroutine ASSIM a photosynthetic-light response curve is used to calculate assimilation rate. This photosynthetic-light response curve holds the term AMAX (actual maximum assimilation rate (kg CO_2 / ha leaf / h)) which is calculated as:

AMAX = AMX * AMTMP

In which AMX stands for the assimilation rate at light saturation (kg CO_2/ ha leaf/ h) measured at 20 °C. The value used in SUCREED for AMX is 50 (kg CO_2/ ha/ h], this is the maximum value for C_3-plants (Spitters, van Keulen & van Kraalingen, 1989). Photosynthesis is an enzymatic-controlled process therefore the rate depends on temperature (DDTMP). Figure 3.2 shows the temperature effect on CO_2-exchange (mg CO_2/ dm^3/ h) of *Phragmites australis*. The effect of temperature on the curve of 320 W/m^2 from figure 3.2 is used to define the temperature effect on assimilation rate in a DATA-table (AMTMPT). AMTMP is a correction factor to adjust AMX for the temperature. Linear interpolation (AFGEN-function) is used to calculate intermediate data.

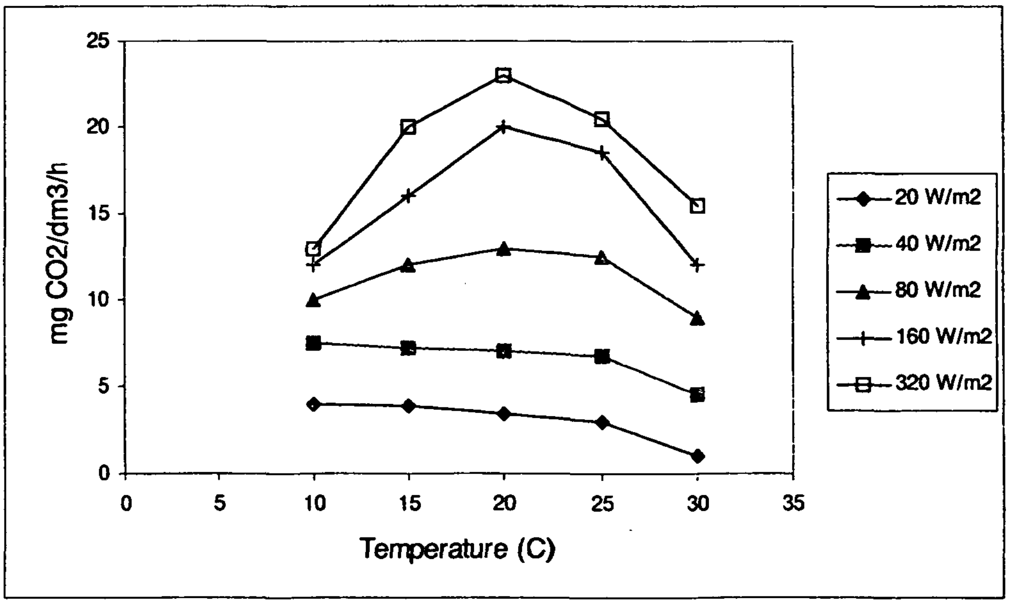

Figure 3.2: Temperature effect on CO_2 uptake in *Phragmites australis* (Ondok & Gloser, 1978)

The DVR depends on daily average temperature (DAVTMP) and DVS. Information on how these tables are calculated can be found in appendix 3.

D 3) Call to ASTRO

More information about subroutine ASTRO can be found in 'Subroutine ASTRO', after the dynamic part.

D 4) Call to TOTASS

This part calls TOTASS to calculate daily total gross assimilation (DTGA), if there is no LAI the daily total gross assimilation (kg CO_2/ ha/ d) (DTGA) equals zero. This condition is only included to speed up the model, so no unnecessary calculations are done. More information on TOTASS, TIDE and ASSIM is given in respectively 'Subroutine TOTASS', 'Subroutine TIDE' and 'Subroutine ASSIM'.

The daily total assimilated kg CO_2/ ha/ d (DTGA) is converted to kg CH_2O/ ha/ d (GPHOT) by multiplying with the molecular mass ratio of 30/ 44.

D 5) Mathematical description of plant processes

```
C*---Remobilization of starch from the rhizomes
   IF (RhRemob(I).GE.0.AND.DVS(I).GE.0.17) THEN
        RGRL = IRGRL
        Remob(I) =  RhRemob(I) * RGRL * DTEFF
        dRhRemob(I) = dRhRemob(I) - Remob(I)
        dRhLive(I)= dRhLive(I) - Remob(I)
     ELSE
        Remob(I) = 0
  END IF
```

In the initialisation part RhRemob (part of initial rhizomes weight to be remobilized) is set, this means remobilization is possible as long as there is DM left in this pool. No remobilization takes place before the DVS equals 0.17, this condition is introduced because growth of the shoots doesn't start before April. The 'start' DVS was found by running the model with different 'start' DVS, to find the one that gave the best fit. As stated in Mayus (1990) remobilization depends on function initial growth rate (RGRL (1/ °C/ d)) and on daily effective temperature (DTEFF). In BGMOD the value of RGRL was found by calibration. DTEFF is calculated as described in D1.

```
C *-- Translocation rate (CH2O/ha/d) of carbohydrates from
C     dying stems
      Trans(I) = StDRate * TransFac * CVT
```

Translocation is transport of carbohydrates from dying stems to mainly the underground organs. From StDRate (kg DW/ ha/ d) a percentage (parameter TransFac) of carbohydrates is translocated. No data were available to estimate TransFac, therefore it was set to the same percentage as found for cassava by Gijzen (1985), namely 30%. The value of CVT is calculated as a conversion from starch to DW (10/9) and transport costs of dry matter (36/38), resulting in a factor of 1.05 (Mayus, 1990).

```
C *-- Maintenance respiration (kg CH2O/ha/d)
      MAINTS = 0.01*StLive(I) + 0.015*RoLive(I) +
               0.015*RhLive(I)
      TEFF   = Q10**((DAVTMP-25.)/10.)
      MAINT  = MIN(GPHOT,(MAINTS * TEFF))
```

Maintenance respiration consists of three components: (i) maintenance of concentration differences across membranes (ii) maintenance of proteins, and (iii) a component related to the intensity of metabolism (Penning de Vries *et al.*, 1989). Typical values for maintenance of stems and roots (also used for rhizomes) are respectively 0.01 and 0.015 (g CH_2O/ g/ d) (Goudriaan & van Laar, 1994). The rate of maintenance is related to temperature, this relation is approximated with the biological concept of a Q_{10}. A Q_{10} of 2.0 is noted as a reasonable value, but lower and higher values are reported (Penning de Vries *et al.*, 1989). The restriction is incorporated that maintenance should not exceed the daily CH_2O production (GPHOT).

D 6) Total growth rate

The fraction of total growth rate (kg DM/ ha/ d) partitioned among the plant organs depends on the DVS, as set in fractionating DATA-tables (e.g. StFracTable) in the initialisation part. The AFGEN-function calculates intermediate values using linear interpolation.

To calculate total growth rate it is necessary to know the assimilate requirements of the several organs for the conversion of CH_2O to DM (ASRQ). Values of 1.46, 1.51 and 1.44 are typical values for respectively stems, roots, and rhizomes (Penning de Vries *et al.*, 1989). Total ASRQ is calculated as:

```
C *---Assimilate requirements for dry matter conversion
      (kg CH2O/ kg DM)
   ASRQ = 1.46*StFr + 1.51*RoFr  + 1.44*RhFr
```

```
C *---Calculation of the total growth rate (TotGrow, kg DM/ha/d)
   TotGrow   = ((GPHOT + TRANS(I) - MAINT) / ASRQ) + Remob(I)
```

The total growth rate is calculated as the sum of sources of CH_2O, minus the maintenance costs, and divided by ASRQ to convert CH_2O to DM. The remobilization is left out of the deviation by ASRQ, because Remob(I) already is expressed as kg DM/ ha/ d.

D 7) Partitioning of TotGrow to organs

The TotGrow (kg DM/ ha/d) is partitioned among the organs depending on the DVS. This dependence is read from the fractionating tables StFracTable, RoFracTable RhFracTable. After partitioning gross growth rates (kg Dm/ ha/ d) of each organs is known.

D 8) Calculation of net growth rates

The relative death rate (e.g. StRDRate) is read from a DATA-table (e.g. StDeathRateTable) and has no unit. To calculate the actual death rate (e.g. StDRate (kg DM/ ha/ d)), the relative death rate has to be multiplied with the living DM weight of the specific organ.
The net growth rate (kg DM/ ha/ d) of the organs is now simply found by subtracting the death rate from the gross growth rate.

D 9) Dry weights of the organs, DVS and LAI

The DM weights of the living and dead plant organs are calculated as the integral of the specific growth/ death rates. For example the StLive(I) is integrated as:

dStLive(I) = dStLive(I) + StNetGrow

```
C *---DVS as integral of DVR
  dDVS(I) = dDVS(I) + DVR
  IF (DVS(I).GE.3.99) THEN
      DVS(I)=3.99
  END IF
```

The new DVS is calculated as the integral of DVR. The restriction that the DVS should not exceed 3.99 is purely for mathematical reasons, because otherwise problems with the AFGEN-function can occur.

```
C *---Calculation of LAI
  StemW = (StLive(I)*0.1) / NPL(I)
  IF (StemW.GT.0) THEN
      IF (StemW.GT.0.16) THEN
          StemL = (56.301*log(StemW) + 117.48) / 100
        ELSE
          StemL = (109.33*StemW)/100
      END IF
      IF (StemW.GT.0.05) THEN
          r = (0.205*log(StemW)+0.7354)/ 200
            ELSE
          r = 0.0005
      END IF
      s = SQRT(r**2 + StemL**2)
    ELSE
      r = 0
      s = 0
    END IF
  LAI(I) = NPL(I) * (PI*r*s) * 0.5
```

First the DW per stem is calculated (StemW (g)), and used in empirical relations between DW and length/ thickness to calculate length and thickness of stem. How these relations are established can be found in appendix 6. The IF-ELSE structure ensures that the valid empirical relation is used for different stem weights. The surface of one stem is calculated assuming a conical shaped stem. The total surface of bulrush per square meter can be found by multiplying with the number of stems per square meter (NPL). The LAI (m^2/ m^2) is found by multiplying the total surface of bulrush with 0.5. Multiplying with 0.5 is necessary like for horizontal leaves the LAI is only the top surface of a leaf.

Subroutine ASTRO

A complete listing of the suboutine ASTRO can be found in appendix 1. Because no modifications were made in this subroutine it is only briefly explained in this report, more information on ASTRO can be found in (Mayus, 1990) and (Kropff & Spitters, 1987).

ASTRO calculates following variables:

- solar constant (SC)
- seasonal offset of sine of solar height (SINLD)
- amplitude of sine of solar height (COSLD)
- astronomical day length (DAYL)
- daily total of sine of solar height (DSINB)
- daily total of effective solar height (DSINBE)

These variables are used by TOTASS.

Subroutine TOTASS

A complete listing of subroutine TOTASS can be found in appendix 1, this subroutine is described below.

TOTASS performs a Gaussian integration (Goudriaan, 1986) by integrating canopy assimilation at five times a day to a daily total gross CO_2 assimilation (DTGA, following next steps:

1. Calculation of point of time and accompanying sine of solar elevation.
2. Fraction of direct (PARDIR) and diffuse (PARDIF) PAR of the daily total radiation, these variables depend among others on solar constant and sine of solar elevation.
3. Call to TIDE, this subroutine calculates the amount of LAI which is flooded (and therefore not available for assimilation) as a result of tide on the Schelde.
4. Now ASSIM is called, this subroutine performs a Gaussian integration over canopy depth, to calculate canopy assimilation; FGROS (kg CO_2/ ha/ h).
5. Integration of canopy assimilation rates in five different times a day to a daily total; DTGA (kg CO_2/ ha/ d).

Subroutine TIDE

Subroutine TIDE calculates water level at a certain time on the Schelde assuming a sine-shaped tidal movement (more information in appendix 7). Due to the actual shape of the tidal movement at Appels, the sine-shaped tidal movement approximation results in an overestimation of the flooding time. This overestimation is taken for granted and no attempt was made to correct for this small error. The water level is compared to the elevation of the bulrush stand, from this the amount of submerged LAI (LAISub) can be calculated. The LAISub is subtracted from the LAI used in the calculation of canopy assimilation rate by ASSIM.

Subroutine ASSIM

Subroutine ASSIM performs a integration of assimilation over canopy depth. In SUCREED the general assumptions of a canopy with a spherical leaf-angle distribution (no preferred leaf-angle orientation) and equal reflection (10%) and transmission (10%) of individual leaves were made. These assumptions lead to relatively simple equations and are suitable for a crop like reed. However considering the canopy characteristics (e.g. leaf-angle distribution, transmission of the leaves) of bulrush this assumption doesn't hold and therefore this subroutine is modified. All modifications are based on Goudriaan (1977), Goudriaan (1988) and Goudriaan & van Laar (1994). In these publications an alternative for the spherical leaf-angle distribution can be found. This alternative is canopy model of that distinguishes three different leaf-angle classes (0-30°, 30-60° and 60-90°). For this model no detailed field data on leaf-angle distributions are necessary, a reasonable guess is sufficient. Goudriaan (1988) and Stockle (1992) compared this model with a more accurate nine leaf-angle class model. They concluded that the three-class model gives satisfying results, needing much less data. Because of the necessary modifications in ASSIM, this subroutine is described in detail.

```
C *---Calculation of average projection of leaves (O)
      O1 = AMAX1(0.26, 0.93*SinB)
      O2 = AMAX1(0.47, 0.68*SinB)
      O3 = 1 - 0.268*O1 - 0.732*O2
      O  = F1*O1 + F2*O2 + F3*O3
      T2DS = F1*0.06 + F2*0.25 + F3*0.467 +
             SinB*SinB*(F1*0.81+F2*0.25- F3*0.4)
      RangeT = SQRT(12. * MAX(0.,T2DS - O*O))
```

The calculation of the average projection of the leaves into the direction of the solar beam (O) is necessary for calculating the extinction coefficient for direct radiation. For a spherical leaf-angle distribution the average projection (O) equals 0.5 (ratio between base of a hemisphere and its surface). For a different leaf-angle distribution, O can be calculated as noted above, it becomes clear that O now depends on the sine of solar elevation (SinB). F1, F2, and F3 stand for the fraction of leaves in the three leaf-angle classes around 15°, 45° and 75°, the sum of F1, F2, and F3 is 1 by definition. The variable T2DS is used to calculate RangeT, which is used in the integration procedure of sunlit leaves over the sky, which is performed later in ASSIM.

Solar radiation can be divided into diffuse and direct radiation. To describe the radiation climate trough the canopy it is necessary to calculate reflection and extinction coefficients for diffuse and direct radiation. The calculation of extinction and reflection coefficients for diffuse and direct radiation differs. In general it can be stated that the coefficients for direct radiation depend on solar elevation, this is not the case for coefficients for diffuse radiation. Therefore coefficients for direct radiation should be calculated every time ASSIM is called (different point of time and thus different solar elevation). The reflection coefficient of diffuse radiation depends only on F1, F2, F3, and is a weighed average of reflection coefficients for direct radiation for different incoming radiation angles. Consequently one calculation is sufficient, therefore this calculation is incorporated in the initialisation part. The extinction coefficient for diffuse radiation depends on F1, F2, F3, and LAI, this calculation is performed in ASSIM. In fact one calculation in TOTASS would be sufficient (LAI is only calculated once a day), for reasons of structure the calculation is performed in ASSIM.

```
C *---Extinction coefficient for direct radiation and total
      direct flux
    KDirBl = (O/SinB)
    KDirT  = KDirBl*SQRT(1-RHO**2)
```

Assuming black leaves, the extinction coefficient (KDirBl) can be calculated. To adapt the extinction coefficient for reflection (transmission of bulrush stems is assumed to be zero), the KDirBl needs to be multiplied with $\sqrt{(1\text{-rho}^2)}$.

```
C *---Reflection coefficient of direct radiation
    RefDir = RefH * 2 * O / (O + SinB)
```

The reflection coefficient for horizontal leaves that reflect but don't transmit (RefH) is calculated in the initialisation part by: $\text{RefH} = (1 - \sqrt{(1 - \text{rho}^2)}) / \text{rho}$
This is the reflection coefficient for horizontal leaves. Actual reflection coefficient for direct radiation (RefDir) depends further on average projection of the leaves (O) and sine of solar elevation (SinB).

```
C *---Extinction coefficient for diffuse radiation
      KDif = (-LOG(0.178*EXP(-K15*LAI)+0.514*EXP(-K45*LAI)
     &       + 0.308*EXP(-K75*LAI)))/LAI
Note: LOG statement in Fortran means natural logarithm
```

The extinction coefficient for diffuse radiation (KDif) depends on K15, K45, K75, and LAI. K15, K45, and K75 are calculated in the initialisation part (see I 3) because they depend only on F1, F2, and F3. Because KDif depends on LAI according to the formula mentioned above it has to be calculated every day. Reflection coefficient for diffuse radiation (RefDif) is calculated in the initialisation part.

Now all the necessary coefficients are calculated, so the integration of assimilation over canopy depth can be performed. No major modifications were implemented in this integration, therefore this part of ASSIM is only described briefly. Detailed information can be found in Goudriaan & van Laar (1994).

The calculation of the assimilation rate differs between sunlit and shaded leaves. Shaded leaves absorb only diffuse radiation, sunlit leaves however absorb also direct radiation resulting in a higher assimilate rate of sunlit leaves. The absorbed diffuse radiation of shaded leaves (VISSHD) is calculated using reflection and extinction coefficients for diffuse radiation and used in the photosynthetic-light response curve to calculate local assimilation of shaded leaves (FGRSH). The absorbed radiation of sunlit leaves (VISSUN) is calculated as the sum of absorbed diffuse radiation and the absorbed direct radiation. Also the absorbed radiation by sunlit leaves is used in a photosynthetic-light response curve to calculate local assimilation of sunlit leaves (FGRSUN). The total local assimilation rate is the sum of assimilation of shaded leaves and assimilation of sunlit leaves. The total local assimilation rates are integrated to a canopy assimilation rate (FGROS).

4 Sensitivity analysis

4.1 Introduction

A sensitivity analysis is performed to investigate for which parameter ranges the model is sensitive. Special interest is paid to parameters that are not measured or for which a wide range is found in literature.

As stated before sensitivity analysis is a standard tool in SENECA. It uses the Monte-Carlo method, this means that parameter values are randomly drawn within a predefined range. The distribution of the parameters was set to 'LH-Uniform', meaning that the parameter range is split up into intervals equal to the amount of runs, from each interval a value is randomly drawn. Each parameter was analysed separately by 50 sensitivity runs.

Besides a sensitivity analysis of parameters it seemed interesting to analyse the sensitivity of the model for the daily total radiation (DTR) and for the elevation of a bulrush stand in the littoral zonation (BLevel). The DTR is a forcing function of the model. Significant higher or lower levels of DTR should influence the aboveground DM development of the bulrush stand. By varying the elevation of the bulrush stand an amount of LAI that is regularly flooded varies. A bulrush stand higher in the littoral zonation is less frequently flooded. This analysis gives an impression on the tidal effect (flooding) on the DM development of a stand higher or lower in the littoral zonation. Daily total radiation and the elevation of a bulrush stand are not suitable to calibrate the model, as these are measured values that are not open to question. Therefore the sensitivity runs are done with the calibrated model.

4.1.1 Parameters

For the sensitivity analysis the next 5 parameters were selected:

- RemobFac: This factor determines the part of the rhizomes that is available for remobilization. Because no data were available to get an estimate of this value a wide range was chosen: 30% - 80%.
- Q_{10}: This parameter accounts for the increase in maintenance respiration for a temperature increase of 10°C. A general Q_{10} value is 2, but lower and higher values are reported (Penning de Vries *et al.*, 1989). No range was mentioned in this publication, the range was set to 1.5 – 2.5.
- Rho: Rho is the reflection coefficient for individual leaves. In general the reflection coefficient is around 10% (Goudriaan & van Laar, 1994). The range was set to 5% - 20%.

- IRGRL: In SUCREED IRGRL stand for the 'relative growth rate during exponential leaf area growth', and was calculated using:

$$IRGRL = (\ln W_2 - \ln W_1) / (TS_2 - TS_1)$$

$W_{1,2}$ = weight of leaves at time 1 or 2

$TS_{1,2}$ = temperature sum at time 1 or 2

  Because bulrush has no leaves, IRGRL was calculated with weights of the stems at time 1 and 2. The value found was 0.00628 (1/ °C/ d). A test run using this value showed that remobilization continued until July. Because remobilization is only expected during springtime, this was not thought to be a realistic value for IRGRL. In order to gain more insight in the effect of IRGRL on the model results, it was tested in the sensitivity analyses. The value used in SUCREED was 0.021, the range was chosen around this value, namely 0.01 - 0.04.
- EFF: EFF stands for 'the initial light use efficiency of individual leaves' and is used in the calculation of assimilation. In SUCREED this parameter was highly sensitive and was therefore also tested in BGMOD. The value used in SUCREED was 0.45 (kg CO_2/ ha/ h)/ (J/ m^2/ s). The range tested in the sensitivity analysis for BGMOD was 0.30 – 0.60.

4.1.2 Daily total radiation

The data on daily total radiation used in the calibration are measured by the KMI (in Dutch: Koninklijk Meteorologisch Instituut van België; Royal Meteorological Institute of Belgium) at Munte (Belgium). Analysing these measured data reveals that especially during the summer the measured radiation is highly variable, see figure 4.1. The short time scale variability is mainly caused by cloudiness. A sine along the highest measured values can be regarded as a cloudless year. While a sine along the lowest measured values approaches a clouded year. To test the sensitivity for radiation three runs were made. One with a sine approach of cloudless year, one with a sine approach of a clouded year, and one average run. The sine approach is obtained with:

$$DTR = SIN(time*360/365*0.5) * Fdtr$$

The parameter Fdtr is the maximum value of the sine and is used to distinguish the three approaches. For the cloudless year Fdtr is $28 \cdot 10^6$, for the clouded year $11 \cdot 10^6$, and $19.5 \cdot 10^6$ for the average year. These sine approaches are only used in the sensitivity analysis of the model for DTR, for sensitivity analysis of the parameters and during calibration the measured DTR values are used. The results of these approaches together with the measured date are presented in figure 4.1.

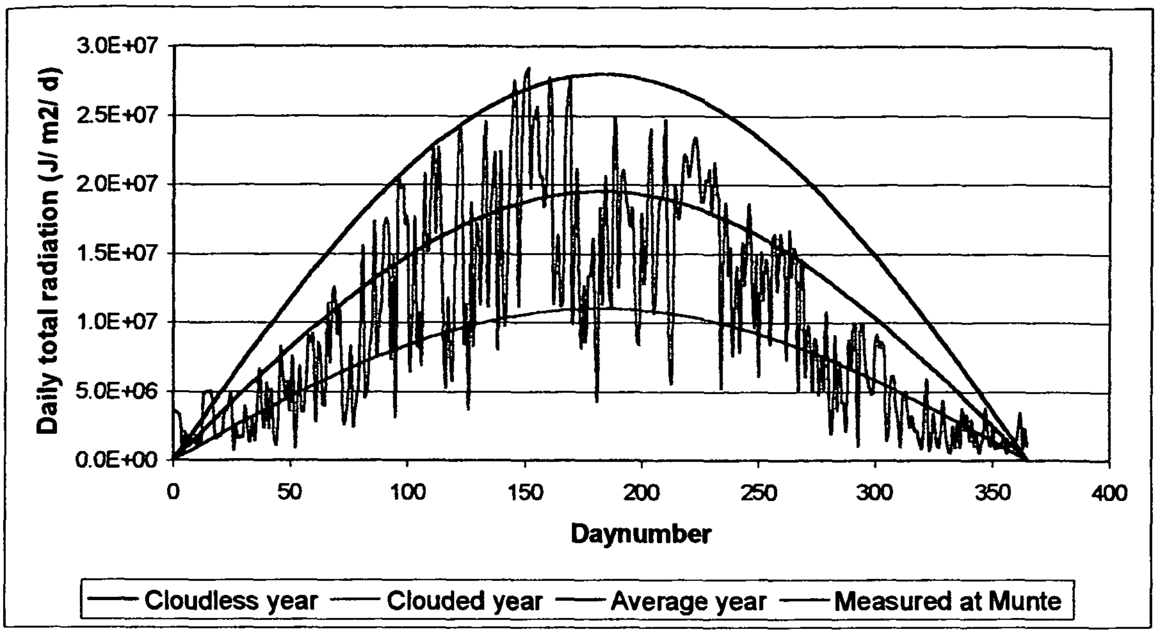

Figure 4.1: Sine approaches of daily total radiation in different situations and measured values at Munte

4.1.3 Elevation of a bulrush stand

Subroutine TIDE calculates the amount of LAI that is submerged as a result of the water level of the Schelde. By varying the elevation of a bulrush stand in the littoral zonation (Blevel), an idea can be obtained about the effect of temporarily flooding on the DM development. The elevation of the bulrush stand from which data (appendix 7) are used is 4.82 m TAW. Information on the sinusoidal approach of the tide as modelled in subroutine TIDE can be found in appendix 7. Following elevations of the bulrush stand were tested; 6.00 m TAW (no flooding), 4.82 m TAW (elevation of the measured bulrush stand), 4.32 m TAW, and 3.82 m TAW.

4.2 Results and discussion

Parameter RemobFac

The remobilization parameter RemobFac seems a sensitive parameter (figure 4.2). Especially in the beginning of the growth season the DM development is sensitive for remobilization. This can be expected because the remobilization process provides the stems in the beginning of the growth season with most of the DM to grow. The smaller the remobilization pool, the lower the initial development. One has to keep in mind that the parameter is sensitive but the range used in the analysis is quit large, from 40% (remobilization pool of 2026 kg DM/ ha) till 80% (remobilization pool of 4051 kg DM/ ha) of the weights of the rhizomes.

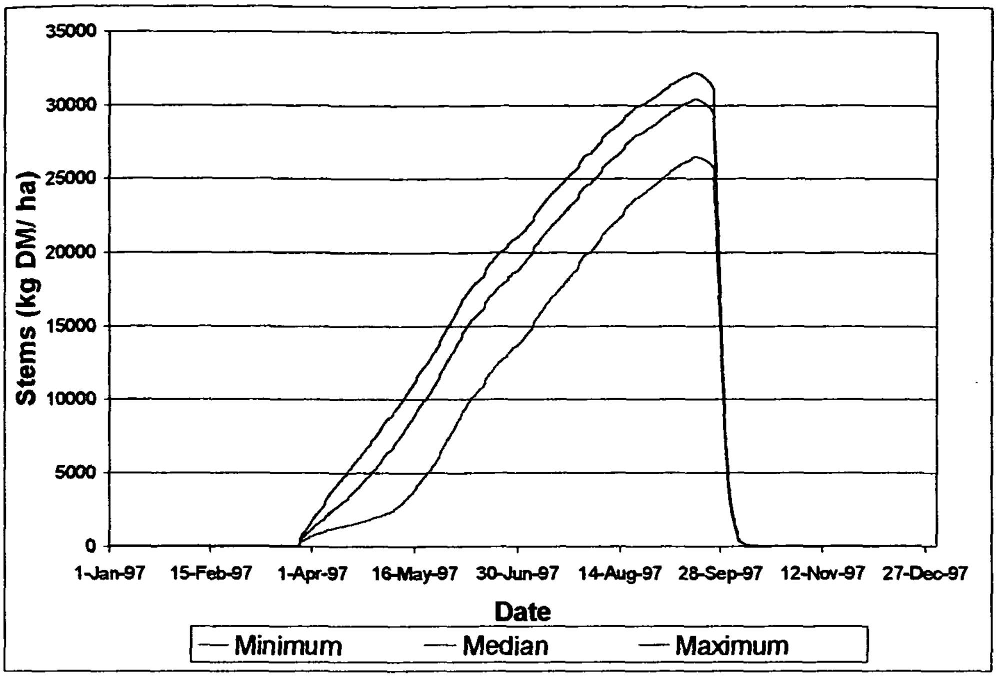

Figure 4.2: Result of the sensitivity analysis of the parameter RemobFac

Parameter Q10

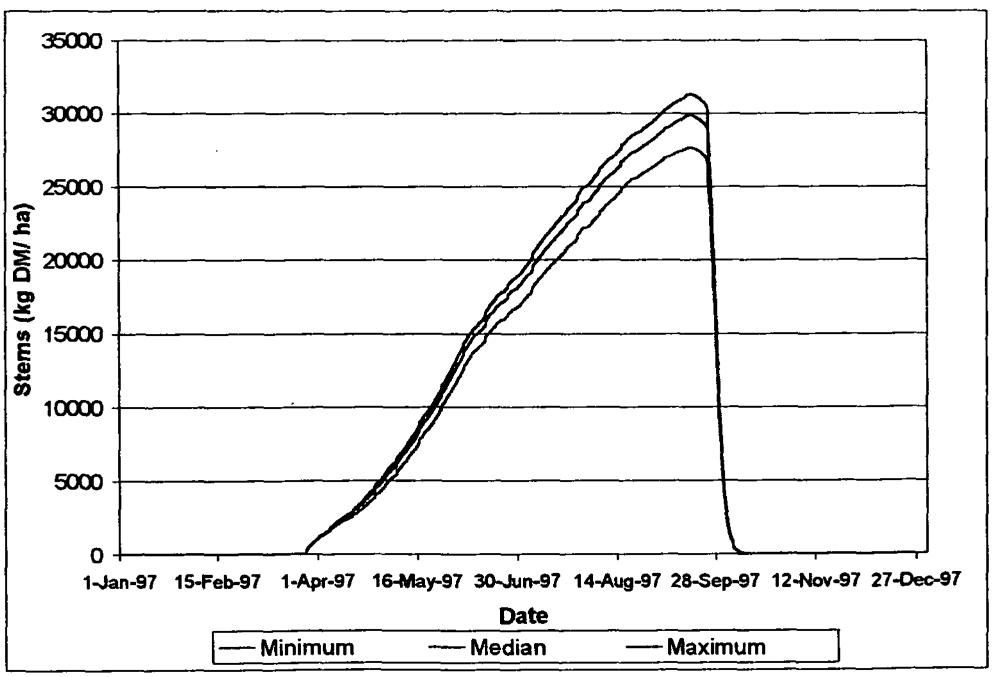

Figure 4.3: Result of the sensitivity analysis of parameter Q_{10}

The parameter Q_{10}, which effects maintenance respiration, can be considered as sensitive (figure 4.3) because the DW development is clearly influenced despite the relative narrow range of 1.5 – 2.5. Due to the use of a Q_{10} concept on maintenance respiration, the relative importance of Q_{10} increases with increasing temperature. Therefore the sensitivity is clearest during summer months.

Parameter Rho

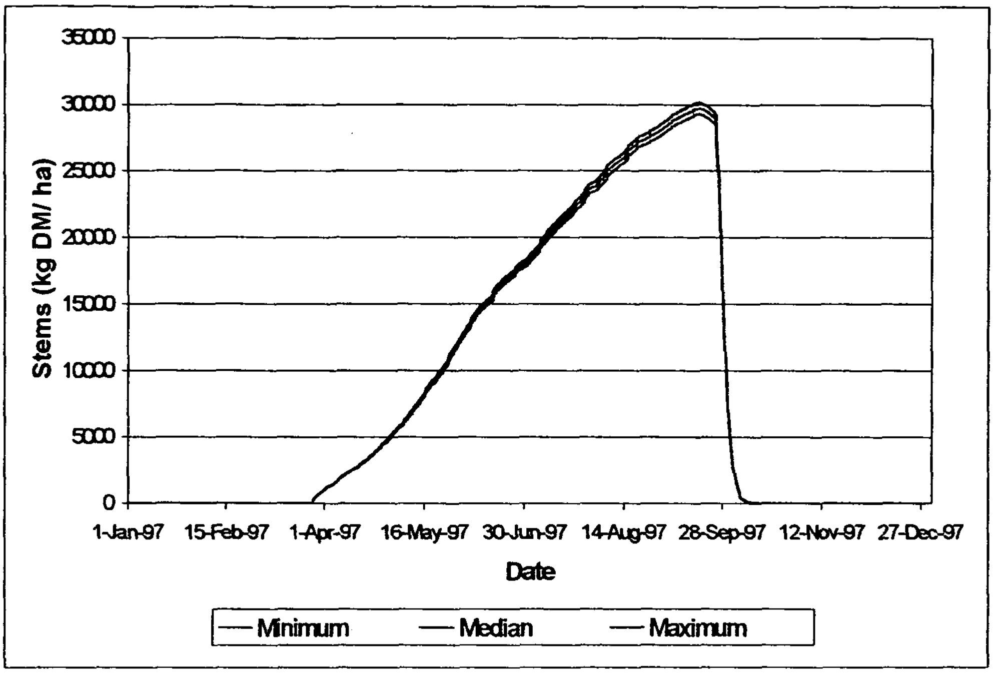

Figure 4.4: Result of the sensitivity analysis of parameter Rho

The effect of a varying Rho (reflection coefficient of individual leaves) on the DM development is very low (figure 4.4), although a reasonable range of 0.05 – 0.20 was tested. Therefore Rho can be considered as not sensitive.

Parameter IRGRL

The sensitivity of the model for the rate of remobilization (IRGRL) is not high (figure 4.5). Especially when the wide range of 0.01 - 0.04 (1/ °C/ d) is taken into account. The relative low remobilization rate effects the DW development only during the remobilization period, and the difference is maintained throughout the growth season.

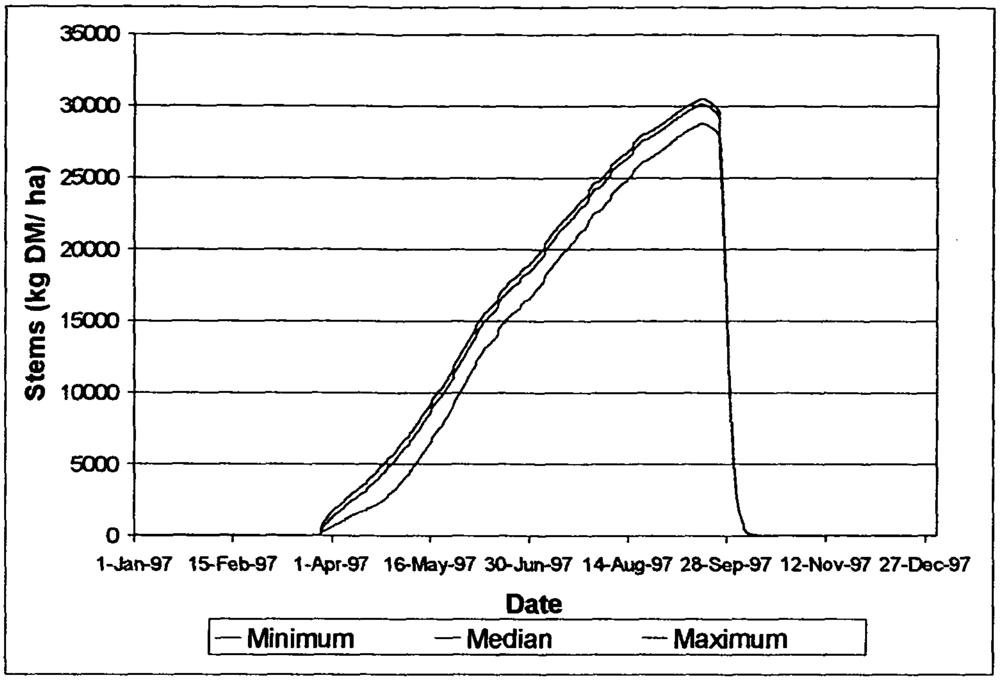

Figure 4.5: Result of the sensitivity analysis of parameter IRGRL

Parameter EFF

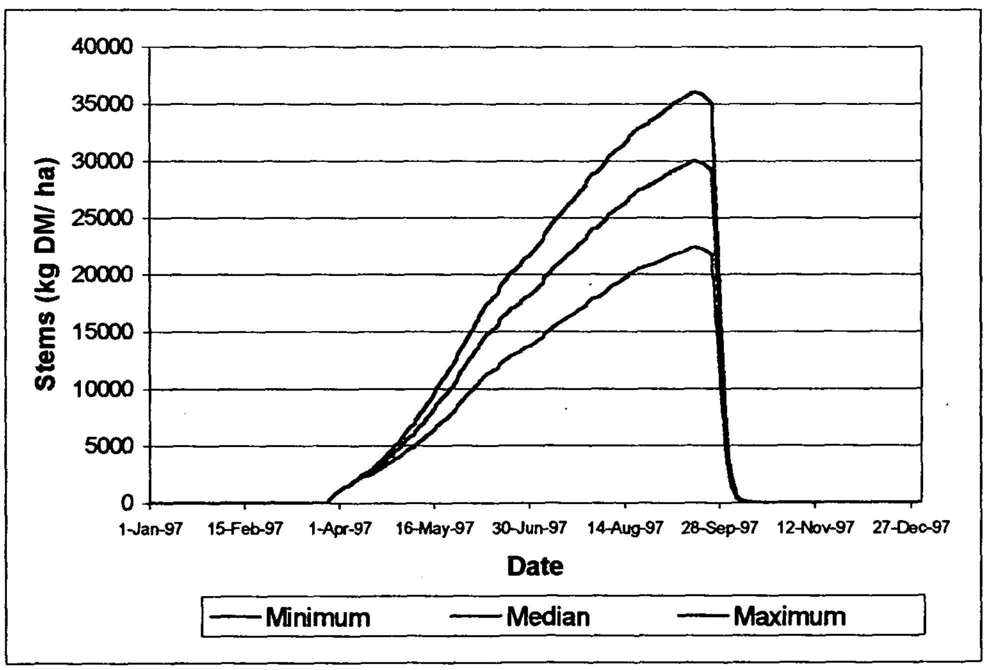

Figure 4.6: Result of the sensitivity analysis of parameter EFF

Parameter EFF can be considered as a very sensitive parameter (figure 4.6), this was also found for SUCREED (Mayus, 1990). The range used in the analysis was

0.30 – 0.60 (kg CO_2/ ha/ h)/ (J/ m^2/ s), which influences the DM development considerably. This can be explained because EFF is the parameter that stands for the efficiency at which the absorbed radiation is used in the assimilation calculation with the photosynthetic-light response curve.

Daily total radiation

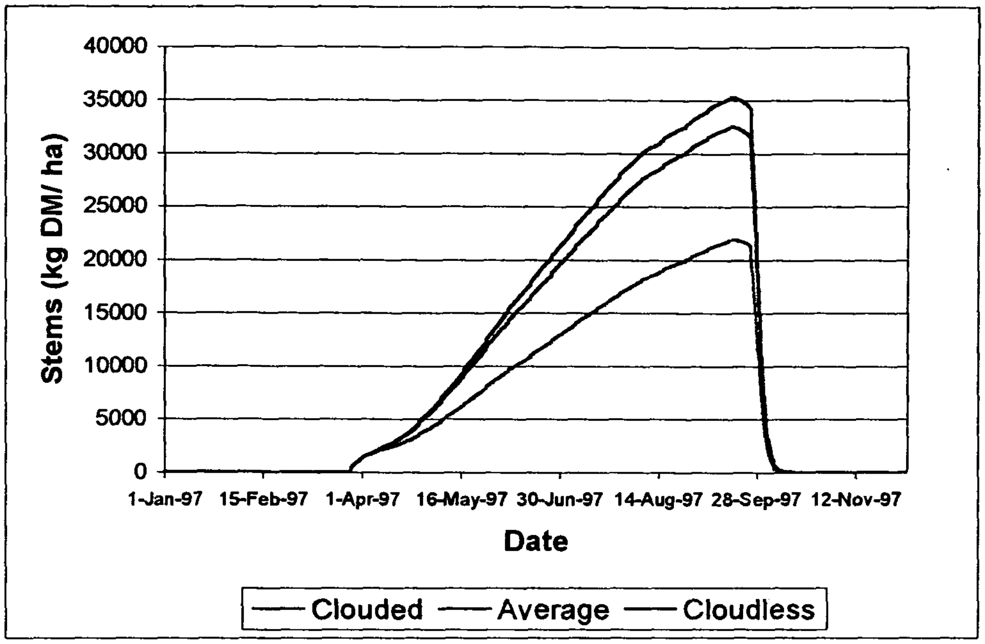

Figure 4.7: Results of different yearly radiation profiles on DM development

The daily total radiation (DTR) is an important forcing function of the model (figure 4.7). Especially the DM development during the 'clouded' year is considerably lower then the DM development of the 'average' and 'cloudless' year. It is however surprisingly that the difference between the 'average' and 'sunny' year is not as pronounced compared to the 'clouded' year. Prpbably the radiation during the 'average' year is close to the light saturation point of bulrush and therefore more radiation has a limited influence on DW development.

Elevation of a bulrush stand

Almost no difference between the DM development of a bulrush stand at 6.00 m TAW (no flooding) and at 4.82 m TAW (elevation of measured bulrush stand) can be observed. This shows that a higher percentage of submerged LAI of a bulrush stand at 4.82 m TAW compared to 6.00 m TAW (table 4.1), has not a large impact on the annual DM development. This can be explained because apparently the remobilization ensures that the new shoots grow high enough to neutralise the tidal effect considerably. Even at 3.82 m TAW, bulrush manages to maintain a relatively high production despite the high frequency of flooding. This result is supported by the property of bulrush to withstand temporarily floods as described in chapter 2.

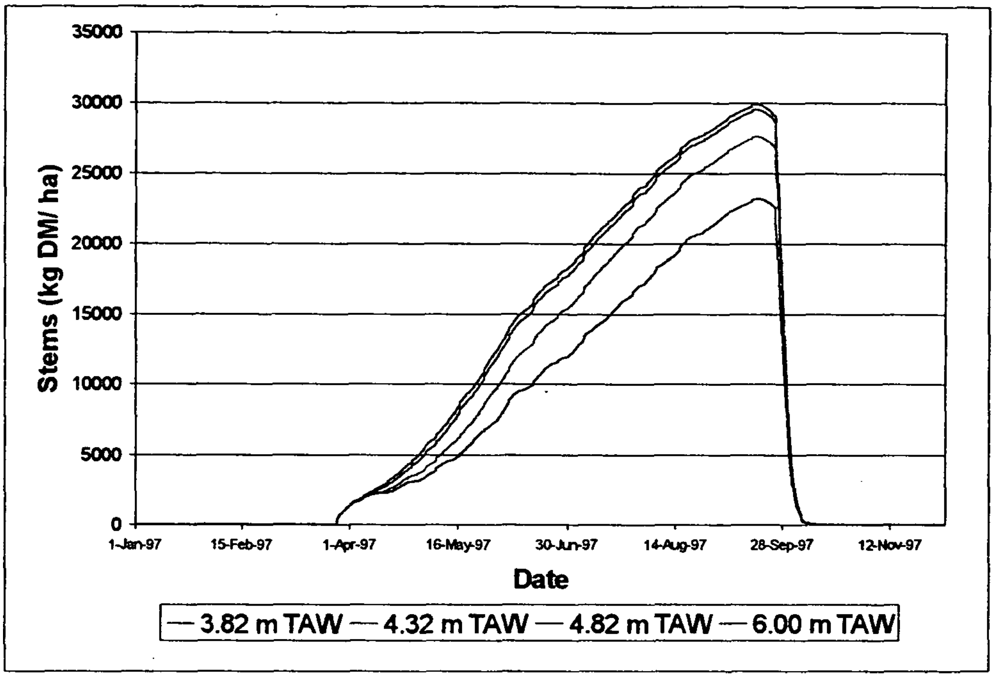

Figure 4.8: Results of different elevations of a bulrush stand on annual DM development

	Percentage of LAI that is submerged at:	
Elevation of bulrush stand (m TAW)	30-May	15-Aug
6.00	0%	0%
4.82	50%	22%
4.32	100%	69%
3.82	100%	97%

Table 4.1: Percentage of submerged LAI of bulrush stands at different elevations at 30 May and 15 August

5 Calibration

5.1 Introduction

For the calibration of the model 750 runs were performed, using the SENECA calibration method of 'controlled random search' (de Hoop *et al.*, 1989). This method searches for an optimum fit storing the parameter values every time a better performance of the model was found. The performance of the model compared to the measured data is expressed in a GoF (Goodness of Fit). When this value equals zero the model fits the measured data perfectly. More information can be found in de Hoop *et al.* (1989).

The model is calibrated using the DW data of living stems from 1997 (appendix 7), because only these data are accurate enough to be used in the calibration. In 1997 the DW of stems were measured 11 times between April and October. After calibration of the model on stem DW, the DW development of roots and rhizomes was roughly calibrated using the death rate tables as discussed in *I 1) Definition of DATA-tables* in chapter 3.

5.2 Parameters used for calibration

In the former chapter the model was analysed for sensitive parameters. From these analysis it was concluded that Rho (reflection coefficient for individual leaves) is not a sensitive parameter, so this is not a suitable parameter to use for calibration.

The parameter Q_{10} (temperature effect on maintenance) was a relative sensitive parameter, but in Penning de Vries (1989) a value of 2 was considered a reasonable guess, therefore it was decided not use the parameter Q_{10} for the calibration.

A very sensitive parameter turned out to be EFF (light use efficiency of individual leaves). Ehleringer & Pearcy (1983) found little variation in EFF among C_3-species, therefore it seems unrealistic to use EFF for the calibration.

IRGRL and RemobFac are parameters related to remobilization, for which no data are available and are fairly sensitive. The parameters IRGRL (rate of remobilization) and RemobFac (percentage of rhizomes available for remobilization) are therefore used for the calibration. The used range equals the range used for the sensitivity analysis, namely 0.01 – 0.04 (1/ °C/ d) for IRGRL and 0.30 – 0.80 for RemobFac.

5.3 Results and discussion

The values of IRGRL and RemobFac that gave the best fit were respectively 0.03841 (1/ °C/ d) and 0.4218. The GoF of this run was 0.1343, which can be considered as a good fit. The model performance is presented in figure 5.1.

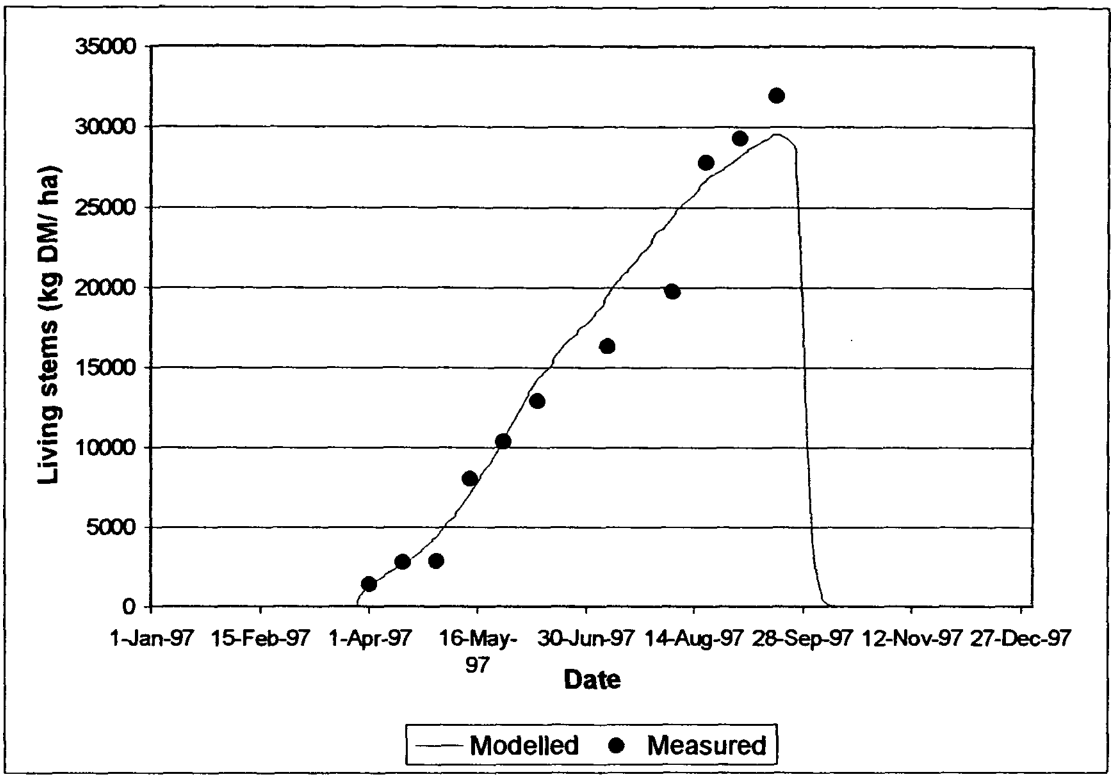

Figure 5.1: Model performance after calibration on stems

The way the data on DW of stems were obtained is not specifically suitable for calibration of this model, because the DW development of individual stems was followed and not the DW development per square meter. Density measurements in April 1999 were used to calculate DW development of stems from 1997 per square meter. It is difficult to judge the effect of this calculation on the data set. Despite this artefact the model performance is good.

The DM development of roots and rhizomes was roughly calibrated using RoDeathRateTable and RhDeathRateTable, both tables can be found in appendix 1. This calibration of roots and rhizomes took place after the calibration of the model on DW of the stems with the parameters RemobFac and IRGRL.
The annual pattern of the measured belowground DM is described reasonable by the model (figure 5.2). Higher accuracy is not necessary regarding the high standard

error of the mean (appendix 7), also considering the few data available on belowground DM. The fast increase of DM of roots and rhizomes at the beginning of October is the result of translocation. The death rates as defined in the RoDeathRateTable and RhDeathRateTable have been adapted manually until a reasonable fit with the DW development of roots and rhizomes was achieved.

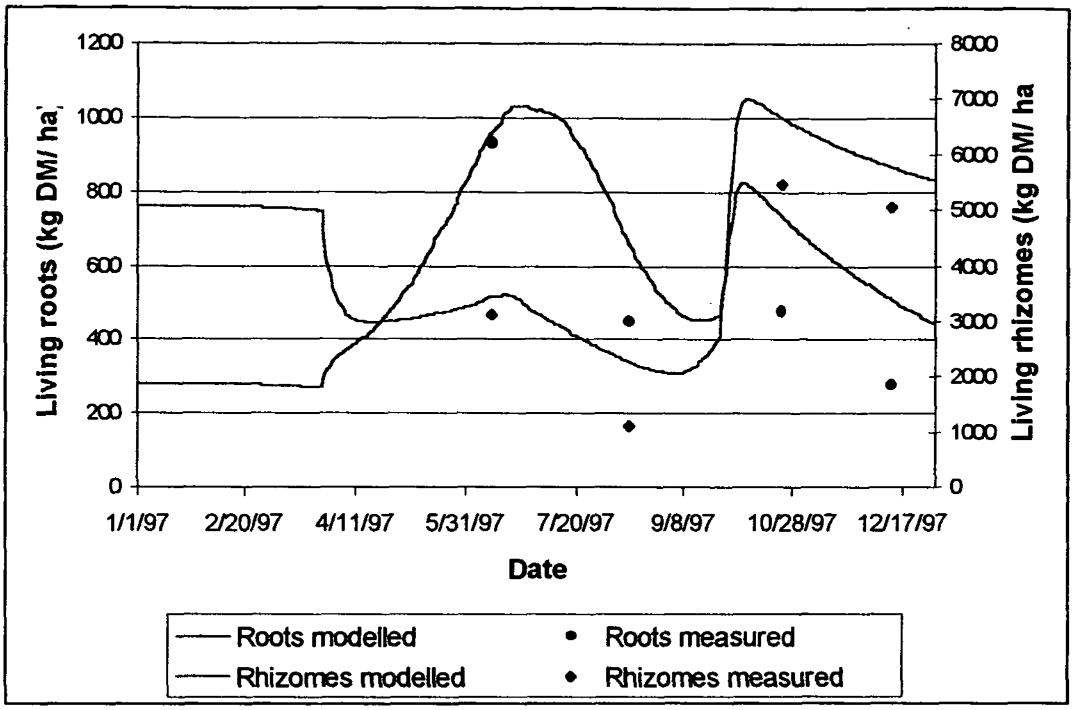

Figure 5.2: Model performance on roots and rhizomes

6 Validation

6.1 Introduction

The model is calibrated based on data obtained in 1997. Data obtained In 1996 at 12/06/1996, 16/07/1996, and 19/08/1996 (appendix 7) on aboveground DM are used to validate the model. The data represent the average stem weight (n = 75) multiplied with the number of stems per square meter (determined at 22/04/1999).

6.2 Results and conclusions

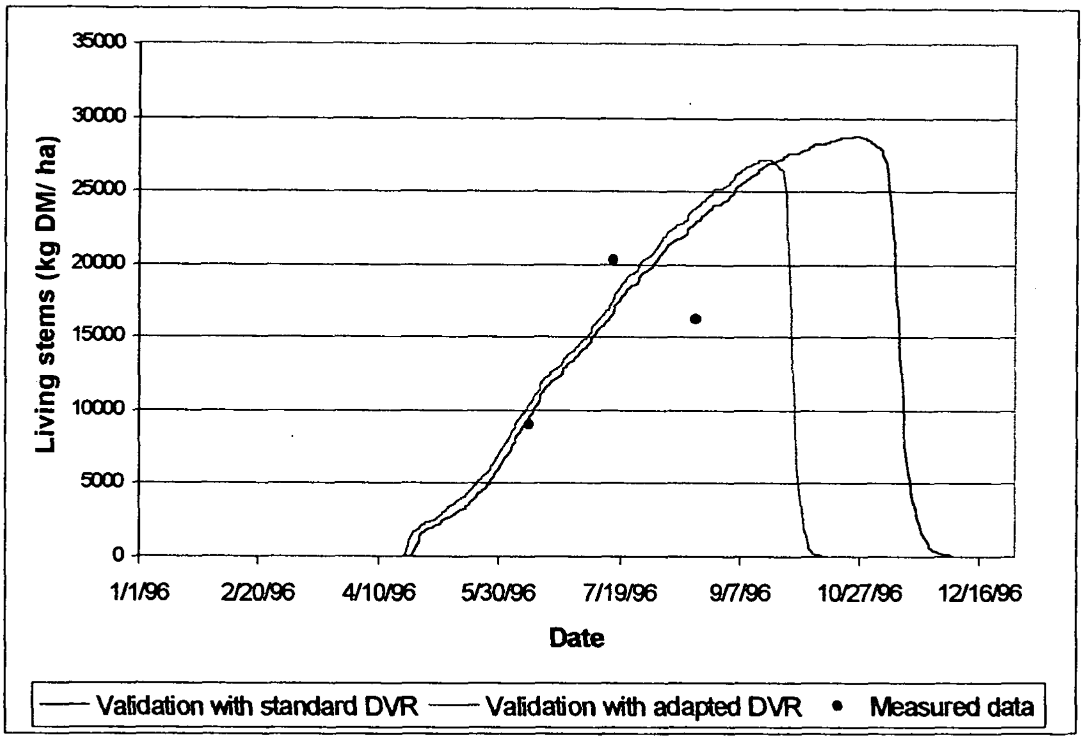

Figure 6.1: Results of the validation on data from 1996

The 'Validation with standard DVR' is the result of a simulation run with the model calibrated for 1997. As can be seen the stems die off during November. This is not a realistic situation along the Schelde, because they die off during September (personal communication Maurice Hoffmann, Institute for Nature Conservation in Brussels). The DVS determines the death rates of the stems, and the development of the DVS depends on daily temperatures. When daily temperatures are lower in 1996 then in 1997, the DVS at a certain date is lower in 1996 then the DVS in 1997. This causes the late die off of the stems in 1996 as described by the model. Despite this artefact the observed data on 12-June and 16-July are described well. The measured DW of the stems in August looks unrealistic because it is lower then the DW halfway July. This is probably due to the sampling method, which is not specifically suitable for this model. For further discussion see appendix 7. A sampling method more suitable for this model is given in chapter 8.

Because of the late die off of the stems as described by the model in 1996 a second validation run was made. For this second run the DVR-tables (development rate) were recalculated with temperature data from 1996, using the procedure as explained in appendix 3. This improves the simulation of the DVS (development state), and consequently the senescence of the stems. Although no data are available too compare the two different validation runs properly, it is imaginable that the 'Validation with adapted DVR'-run gives a better result. This implicates that the present use and calculation of a DVS only depending on temperature is debatable. Apparently because temperature can differ considerably over the years. Therefore the use of new calculation method for DVS based on a combination of temperature and day length would give better results,

7 Conclusions

Conclusions regarding research questions

The canopy of bulrush can be described theoretically using following assumptions:

- The stems (acting as leaves) of bulrush reflect radiation, transmittance is assumed to be zero;
- The leaf-angle distribution of the canopy of bulrush can be modelled using three leaf-angle classes, which makes it possible to model an erectophile canopy;
- The Leaf Area Index of bulrush can be calculated based on the surface of the 'leafless' stems.

The growth of bulrush can be modelled by distinguishing the organs: stems, roots and rhizomes. The development rate of bulrush can be calculated using temperature measurements and by choosing several phenological development stages through the year. For partitioning of DW among the plant organs the ratio of DW (dry weights) at several times through the year can be used.

Conclusions regarding model performance

The sensitivity analysis revealed that parameter EFF (light use efficiency of individual leaves) is a sensitive parameter, but a good estimate could be made based on literature. The amount of dry weight available for remobilization is a fair sensitive parameter, for which no estimate could be made. The model was not very sensitive for the rate of remobilization.

The model performance on DW of stems after calibration is good (Goodness of Fit = 0.134). Although the sampling method was not intent to provide data for the calibration procedure, the model describes the data well. A proper validation could not be performed, however the validation on the available data showed reasonable results.

The model takes effect of temporarily floods of Leaf Area Index due to tidal movement of the Schelde on assimilation into account. The property of bulrush to withstand temporarily floods was supported by the model results, because floods didn't effect DW development of stems severely.

An important but weak feature in the model is the description of the phenological development of the plant by development stages that only depend on temperature. The development stages are calculated using the temperature sum over a period of time. Because temperature (and consequently also temperature sum) can differ considerably between years, the development of the plant is not accurately described when during validation development rate tables based on other years are used.

8 Recommendations

8.1 Recommendations regarding the model

- It was found that the daily total radiation is an important forcing function of the model. In subroutine ASTRO and TOTASS the amount of direct and diffuse PAR are calculated based on standard procedure (Goudriaan & van Laar, 1994). Alados *et al.* (1996) describes a method to find empirical relations that could be used to estimate amount of PAR from measured broadband solar radiation. The variables used in the empirical relations are commonly measured radiometric variables. This method could provide a more accurate way of calculating daily amount PAR.
- The feature of the model of describing the phenological development of the plant using temperature related development stages (DVS) is debatable because of temperature differences between years. This method should be replaced by a method that calculates the DVS of the plant using temperature and day length so the effect of temperature differences is tempered.

8.2 Recommendations regarding field research

- Important to calculate the LAI of bulrush are the relations between DW and thickness/ length of stems. The relations used in the model are based on a limited amount of data obtained at a temperature, light and humidity controlled experiment or at the field during summer. In order to obtain a suitable data set a sampling campaign was started in April 1999, the preliminary results could not yet be implemented in this model. It is recommended to continue this campaign through the whole growth season of bulrush.
- The method used to obtain data on DW development of bulrush is not specifically suitable to use as calibration data for this model. A better method would be to follow annual DW development on a permanent quadrant using a non-destructive method. Within this permanent quadrant the number of stems should be counted and length and thickness should be measured. Other stems surrounding (preferably at the same level as the stems in the quadrant) the quadrant should be clipped and used to set up a relation between DW and thickness/ length of a stem. Within this method it is also possible to follow death rates of stems during the season, so far no data were available to count for this.
- Measured data of reed on the effect of temperature on maximum assimilation rate (AMTMP) as well as maximum assimilation rate at light saturation (AMX)

were used in this model. Preferably experiments should be conducted to find AMTMP and AMX for bulrush.

9 Literature

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Appendix 1: Listing of bulrush growth model (BGMOD)

```
##################################################################
 SENECA 2.0                                         (C) NIOO-CEMO/DGW
C File: "submodel".FOR
C Date: 1-3-93
##################################################################
      SUBROUTINE REEDGROW(TIME)
C
C
      IMPLICIT   NONE
  Parameter:
      DOUBLE PRECISION TIME
C the parameter TIME contains the simulation time
C the simulation time is expressed in the model's Time Unit
  and is relative to the start date/time of the simulation period
  so at the start of the simulation, when this subroutine is
C called for the first time, TIME equals 0.0
C after every integration step TIME is increased with the amount
  of the integration step size.
 ----------------------------------------------------------------
  External functions
      EXTERNAL AFGEN

  Declarations:
      INCLUDE 'REED.DCS'
      INCLUDE 'REEDGROW.DCP'
      INCLUDE 'REEDGROW.DCV'
      INCLUDE 'XSIMO.DEX'
      include 'xcommat.all'
 ----------------------------------------------------------------

*****************************************************************
                                                                *
  STRUCTURE OF MODEL                                            *
================================================================*
*     INITIALIZATION                                            *
          1 Definition of DATA-tables                           *
          2 Setting start values for state variables            *
          3 Calculation of diffuse light related parameters     *
*===============================================================*
*     DYNAMIC                                                   *
          1 Reading of temperature and daily radiation          *
          2 Calculation of AMAX and DVR                         *
          3 Call ASTRO                                          *
*         4 Call TOTASS                                         *
          5 Plant processes                                     *
          6 Total growth rate                                   *
          7 Partitioning of total growth rate among plant organs *
*         8 Net growth rate of organs                           *
*         9 Integration of state variables and LAI              *
================================================================*
      SUBROUTINES                                               *
          ASTRO                                                 *
*         TOTASS                                                *
          ASSIM                                                 *
          TIDE                                                  *
*****************************************************************
      INTEGER I,Ncomp,DAY
      DOUBLE PRECISION  AFGEN,AMAX,AMTMP,ASRQ,DAVTMP,DAYL,DDTMP,DSO,
     &DSINB,DSINBE,DTEFF,DTGA,DTMAX,DTMIN,DVR,MAINTS,PI,r,RGRL,s,
     &RhGrGrow,RhDRate,RhFr,RhNetGrow,RhTot,RhRDRate,
     &RoGrGrow,RoDRate,RoFr,RoNetGrow,RoTot,RoRDRate,
     &StGrGrow,StDRate,StFr,StNetGrow,StTot,StRDRate,StemL,StemW,
     &TEFF,TotDead,TotLive,TotW,
     &FGROS,
     &LAISub,
     &REFH,RefDif,D1,D2,D3,D,X,KDif,K15,K45,K75,
     &Y(3),W(3),
     &SC,SINLD,COSLD, AMTMPT(8,2),
     & DVR0to1(4,2), DVR1to2(4,2), DVR2to3(4,2),DVR3to4(4,2),
     &StFracTable(8,2), RoFracTable(8,2), RhFracTable(8,2),
     &StDeathRateTable(5,2),RoDeathRateTable(9,2),RhDeathRateTable(9,2)
      PARAMETER (PI=3.141592654    )
       SwitchOmex=1
       Ncomp = (XNCOMP)
```

```
C*******************************************************************C
C                                                                   C
C***********          INITIALISATION          ************************C
C                                                                   C
C*******************************************************************C

*======================== Initialisation 1 ========================*

C *---Effect of daytime temperature on AMX (max assimilation rate)
      DATA AMTMPT /-15.,0.00001, -3.,0.00001, 0.,0.00001,
     & 5.,0.35, 22.,1., 33.,0.5, 35.,0.3, 50.,0.01/

C *---Development rate (1/d)
      DATA DVR0to1 / -15.,0., 3.,0., 25.,0.0132, 30.,0.0132 /
      DATA DVR1to2 / -15.,0., 3.,0., 25.,0.0394, 30.,0.0394 /
      DATA DVR2to3 / -15.,0., 3.,0., 25.,0.0621, 30.,0.0621 /
      DATA DVR3to4 / -15.,0., 3.,0., 25.,0.0486, 30.,0.0486 /

C *---Fraction of total dry matter growth to stems (StFracTable),
C      to roots (RoFracTable) and to rhizomes (RhFracTable)
C      as a function of DVS
      DATA StFracTable /0.,0.9,  0.48,0.9, 0.59,0.7637, 0.79,0.8451,
     & 1.42,0.9411, 2.04,0.9141, 3.45,0., 3.999,0. /
      DATA RoFracTable /0.,0.05, 0.48,0.05, 0.59,0.0544, 0.79,0.0377,
     & 1.42,0.0170, 2.04,0.0143, 3.45,0.0806, 3.999,0.0522 /
      DATA RhFracTable /0.,0.05, 0.48,0.05, 0.59,0.1819, 0.79,0.1172,
     & 1.42,0.0419, 2.04,0.0716, 3.45,0.9194, 3.999,0.9478/

C *---Relative death rate of stems (StDeathRateTable), roots (RoDeathRateTable)
C      and rhizomes (RhDeathRateTable) (1/d) as a function of DVS.
      DATA StDeathRateTable /0.,0., 2.5,0., 2.8,0.01, 3.,0.5, 3.999,0.5/
      DATA RoDeathRateTable /0.,0.0, 0.6,0.005, 1.1,0.025, 1.8,0.018,
     &2.5,0.012, 2.75,0.012, 2.78,0.011, 2.8,0.008, 3.999,0.007/
      DATA RhDeathRateTable /0.,0., 0.5,0.002, 0.7,0.018, 1.8,0.007,
     &2.5,0.008, 2.75,0.007, 2.78,0.006, 2.8,0.005, 3.999,0.002/

C *---DO-statement to run model for different compartments (1 in BGMOD)
      DO 100 I = 1, Ncomp

C *---Function to determine the day during the calculation
      DAY = dMOD(TIME,365.0d0)

*======================== Initialisation 2 ========================*

      IF (TIME.GE.RESET.OR.TIME.EQ.0) THEN

C *---Initialization of start values for organs of bulrush
* Stems
      StLive(I)  = IStLive(I)
      StDead(I)  = IStDead(I)
      LAI(I)     = ILAI(I)
* Roots
      RoLive(I)  = IRoLive(I)
      RoDead(I)  = IRoDead(I)
* Rhizomes
      RhLive(I)  = IRhLive(I)
      RhDead(I)  = IRhDead(I)
* Amount of starch in rhizomes available for remobilization
      RhRemob(I) = RemobFac*RhLive(I)

C *---Reset DVS, DVR en temperature sum
      DVS(I) = 0.
      TMPSUM(I) = 0
      DVR= 0.

*======================== Initialisation 3 ========================*

C *---Reflection coefficient for horizontal leaves (RefH), K15, K45, K75
      RefH = (1.-SQRT(1.-RHO**2))/ RHO
      K15 = SQRT(1.-RHO**2)*(1.00*F1 + 1.82*F2 + 2.26*F3)
      K45 = SQRT(1.-RHO**2)*(0.93*F1 + 0.68*F2 + 0.67*F3)
      K75 = SQRT(1.-RHO**2)*(0.93*F3 + 0.65*F2 + 0.29*F3)

C *---Reflection coefficient for diffuse radiation (RefDif)
      DATA Y/15,45,75/
      DATA W/0.178,0.514,0.308/
      RefDif = 0.
      DO 5 X = 1, 3
```

```
      D1 =  AMAX1(0.26, 0.93*SIND(Y(X)))
      D2 =  AMAX1(0.47, 0.68*SIND(Y(X)))
      D3 =  1 - 0.268*D1 - 0.732*D2
      D  =  F1*D1 + F2*D2 + F3*D3
      RefDif = RefDif + W(X) *(RefH * 2. * D) / (D + SIND(Y(X)))
     CONTINUE
     END IF

C*********************************************************************C
C                                                                     C
C***********              DYNAMIC           *************************C
C                                                                     C
C*************************************************************** ****C

*======================= Dynamic 1 ================================*

C *---Daily radiation (DTR) (J/m2/d)
      DTR = (DTRT(time) * 1.E6)

C *---Daily temperature (degree C): maximum, minimum, average, daytime,
     effective
      DTMAX  = TMAXT(time)
      DTMIN  = TMINT(time)
      DAVTMP = 0.5 * (DTMAX+DTMIN)
      DDTMP  = DTMAX - 0.25 * (DTMAX-DTMIN)
      DTEFF  = AMAX1(0.,DAVTMP-TBASE)

*======================= Dynamic 2 ================================*

C *---Maximum assimilation at light saturation (kg CO2/ha leaf/h)
      AMTMP  = AFGEN(AMTMPT,16,DDTMP,'DDTMP')
      AMAX   = AMX * AMTMP
      AMAX   = dMAX1(0.00001d0,AMAX)

C *---Calculation of a new DVR
     IF (DVS(I).LE.1.) THEN
         DVR = AFGEN (DVR0to1,8,DAVTMP,'DAVTMP')
       ELSE IF (DVS(I).GT.1. .AND. DVS(I).LE.2) THEN
         DVR = AFGEN (DVR1to2,8,DAVTMP,'DAVTMP')
       ELSE IF (DVS(I).GT.2. .AND. DVS(I).LE.3) THEN
         DVR = AFGEN (DVR2to3,8,DAVTMP,'DAVTMP')
       ELSE IF (DVS(I).GT.3. .AND. DVS(I).LE.4) THEN
         DVR = AFGEN (DVR3to4,8,DAVTMP,'DAVTMP')
     END IF

*======================= Dynamic 3 ================================*

C *---Calculation of astronomic and photoperiodic daylength
      CALL ASTRO(SC,DS0,SINLD,COSLD,DAYL,DSINB,DSINBE,DAY,LAT(I))


*======================= Dynamic 4 ================================*

C *---Daily total gross assimilation (DTGA, kg CO2/ha/d)
     IF (LAI(I).NE.0) THEN
         CALL TOTASS(SC,DAYL,SINLD,COSLD,DSINBE,DTR,RHO,AMAX,EFF,KDIF,
    &    LAI(I),DTGA,FGROS,f1,f2,f3,RefH,RefDif,K15,K45,K75,
    &    DAY,LAISub,StemL,r,TideSw,AWL,ASWL,ANWL,HSWL,HNWL,BLevel,
    &    NPL(I))
     ELSE
         DTGA = 0
     END IF

C *---Conversion from assimilated CO2 to CH2O
      GPHOT = DTGA * 30./44.

*======================= Dynamic 5 ================================*

C *---Remobilization of starch from the rhizomes
     IF (RhRemob(I).GE.0.AND.DVS(I).GE.0.17) THEN
         RGRL = IRGRL
         Remob(I) =  RhRemob(I) * RGRL * DTEFF
         dRhRemob(I) = dRhRemob(I) - Remob(I)
         dRhLive(I)= dRhLive(I) - Remob(I)
       ELSE
         Remob(I) = 0.
```

```
      END IF

C *---Translocation rate (CH2O/ha/d) of carbohydrates from dying stems
       Trans(I) = StDRate * TransFac * CVT

C *---Maintenance respiration (kg CH2O/ha/d)
       MAINTS = 0.01*StLive(I) + 0.015*RoLive(I) + 0.015*RhLive(I)
       TEFF   = Q10**((DAVTMP-25.)/10.)
       MAINT  = MIN(GPHOT,(MAINTS * TEFF))

*======================== Dynamic 6 ================================*

C *---Fraction to GTW to stems (StFr), roots (RoFr) and rhizomes (RhFr)
       StFr = AFGEN(StFracTable,16,DVS(I),'DVS(I),StFr')
       RoFr = AFGEN(RoFracTable,16,DVS(I),'DVS(I),RoFr')
       RhFr = AFGEN(RhFracTable,16,DVS(I),'DVS(I),RhFr')

C *---Assimilate requirements for dry matter conversion (kgCH2O/kgDM)
       ASRQ = 1.46*StFr + 1.51*RoFr  + 1.44*RhFr

C *---Calculation of the total growth rate (TotGrow, kg DM/ha/d)
       TotGrow   = ((GPHOT + TRANS(I) - MAINT) / ASRQ) + Remob(I)

*======================== Dynamic 7 ================================*

C *---Partitioning of TotGrow
       StGrGrow  = StFr * TotGrow
       RoGrGrow  = RoFr * TotGrow
       RhGrGrow  = RhFr * TotGrow

*======================== Dynamic 8 ================================*

C *---Death rate of stems, roots and rhizomes (kg DM/ha/d)
* Stems
       StRDRate  = AFGEN (StDeathRateTable,10,DVS(I),'DVS(I)')
       StDRate  = StLive(I) * StRDRate
* Roots
       RoRDRate = AFGEN (RoDeathRateTable,18,DVS(I),'DVS(I)')
       RoDRate = RoLive(I) * RoRDRate
* Rhizomes
       RhRDRate = AFGEN (RhDeathRateTable,18,DVS(I),'DVS(I)')
       RhDRate = RhLive(I) * RhRDRate

C *---Net growth rate of stems (StNetGrow), roots (RoNetGrow) and rhizomes (RhNetGrow)
       StNetGrow = StGrGrow - StDRate
       RoNetGrow = RoGrGrow - RoDRate
       RhNetGrow = RhGrGrow - RhDRate

C Temperature sum after 1.January
       dTMPSUM(I) = dTMPSUM(I) + AMAX1(0.,DAVTMP - TBASE)

*======================== Dynamic 9 ================================*

C *---Dry weights of organs (kg DM/ha) as integrals of growth rates
* Stems
       dStLive(I)   = dStLive(I) + StNetGrow
       dStDead(I)   = dStDead(I) + StDRate - Trans(I)
       StTot        = StLive(I) + StDead(I)
* Roots
       dRoLive(I)   = dRoLive(I) + RoNetGrow
       dRoDead(I)   = dRoDead(I) + RoDRate
       RoTot        = RoLive(I)  + RoDead(I)
* Rhizomes
       dRhLive(I)   = dRhLive(I) + RhNetGrow
       dRhDead(I)   = dRhDead(I) + RhDRate
       RhTot        = RhLive(I)  + RhDead(I)

C *---DVS as integral of DVR
       dDVS(I) = dDVS(I) + DVR
      IF (DVS(I).GE.3.99) THEN
          DVS(I)=3.99
      END IF

C *---Calculation of LAI
      StemW = (StLive(I)*0.1) / NPL(I)
      IF (StemW.GT.0) THEN
          IF (StemW.GT.0.16) THEN
              StemL = (56.301*log(StemW) + 117.48) / 100
            ELSE
```

```
            StemL = (109.33*StemW)/100
          END IF
          IF (StemW.GT.0.05) THEN
            r = (0.205*log(StemW)+0.7354)/ 200
           ELSE
            r = 0.0005
          END IF
          s = SQRT(r**2 + StemL**2)
        ELSE
          r = 0
          s = 0
        END IF

        LAI(I) = 0.5 * NPL(I) * (PI*r*s)

C *---Calculation of several total weights
        TotW      = StTot      + RoTot      + RhTot
        TotLive   = StLive(I) + RoLive(I) + RhLive(I)
        TotDead   = StDead(I) + RoDead(I) + RhDead(I)


100     continue

      IF (TIME.EQ.0) THEN
         RESET=365
      END IF

      IF (TIME.GE.RESET) THEN
         RESET=RESET+365
      END IF
      END



*---------------------------------------------------------------------*
*  SUBROUTINE ASTRO                                                    *
*  Authors: Daniel van Kraalingen                                      *
*  Date   : 9-Aug-1987                                                 *
*  Modified by Jan Goudriaan 4 Febr 1988                               *
*  Modified by Jan Goudriaan and Kees Spitters 7 December 1989         *
*  Purpose: This subroutine calculates astronomic daylength and        *
*           photoperiodic daylength. (see CABO-TPE report #?)          *
*           and diurnal radiation characteristics such as daily       *
*           integral of sine of solar elevation, solar constant        *
*           Measured daily total of global radiation is used to find *
*           atmospheric transmissivity and fraction diffuse radiation*
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name    meaning                                      units  class   *
*  ----    -------                                      -----  -----   *
*  DAY     Day number (Jan 1st = 1)                       -      I     *
*  LAT     Latitude of the site                        degrees   I     *
*  DTR     Measured daily total global radiation       J m-2 d-1 I     *
*  SC      Solar constant                              J m-2 s-1 O     *
*  DSO     Daily extraterrestrial radiation            J m-2 d-1 O     *
*  SINLD   Seasonal offset of sine of solar height        -      O     *
*  COSLD   Amplitude of sine of solar height              -      O     *
*  DAYL    Astronomical daylength (base = 0 degrees)      h      O     *
*  DSINB   Daily total of sine of solar height            s      O     *
*  DSINBE  Daily total of effective solar height          s      O     *
*                                                                      *
*  FATAL ERROR CHECKS (execution terminated, message)                  *
*  condition                                                           *
*                                                                      *
*  LAT > 67, LAT < -67                                                 *
*                                                                      *
*  SUBROUTINES and FUNCTIONS called : none                             *
*                                                                      *
*  FILE usage : none                                                   *
*---------------------------------------------------------------------*
        SUBROUTINE ASTRO (SC,DSO,SINLD,COSLD,DAYL,DSINB,
     &DSINBE,DAY,LAT)

      IMPLICIT NONE

      DOUBLE PRECISION SC,DSO,SINLD,COSLD,DAYL,DSINB,DSINBE,LAT
      INTEGER DAY
      DOUBLE PRECISION PI, RAD,DEC,AOB
      PARAMETER (PI=3.141592654, RAD=0.017453292)

C *-----check on input range of parameters
      IF (LAT.GT.67.)  STOP 'ERROR IN ASTRO: LAT > 67'
```

```
      IF (LAT.LT.-67.) STOP 'ERROR IN ASTRO: LAT <-67'

C *-----declination of the sun as function of daynumber (DAY)
      DEC = -ASIN(SIN(23.45*RAD)*COS(2.*PI*(DAY+10.)/365.))

C *-----SINLD, COSLD and AOB are intermediate variables

      SINLD = SIN(RAD*LAT)*SIN(DEC)
      COSLD = COS(RAD*LAT)*COS(DEC)
      AOB   = SINLD/COSLD

C *-----daylength (DAYL)

      DAYL  = 12.0*(1.+2.*ASIN(AOB)/PI)

      DSINB = 3600.*(DAYL*SINLD+24.*COSLD*SQRT(1.-AOB*AOB)/PI)
      DSINBE= 3600.*(DAYL*(SINLD+0.4*(SINLD*SINLD+COSLD*COSLD*0.5))+
     &      12.0*COSLD*(2.0+3.0*0.4*SINLD)*SQRT(1.-AOB*AOB)/PI)

C *-----solar constant (SC) and daily extraterrestrial (DS0)
      SC  = 1370.*(1.+0.033*COS(2.*PI*DAY/365.))
      DS0 = SC*DSINB
      RETURN
      END
*---------------------------------------------------------------------*
*  SUBROUTINE TOTASS                                                  *
*  Authors: Daniel van Kraalingen                                     *
*  Date   : 10-Dec-1987                                               *
*  Modified by Jan Goudriaan 5-Febr-1988                              *
*  Modified by Jan Goudriaan and Kees Spitters 7 December 1989        *
*  Purpose: This subroutine calculates daily total gross              *
*           assimilation (DTGA) by performing a Gaussian integration  *
*           over time. At three different times of the day,           *
*           radiation is computed and used to determine assimilation  *
*           whereafter integration takes place.                       *
*           (see CABO-TPE report) #?).                                *
*                                                                     *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)    *
*  name     meaning                                      units  class *
*  ----     -------                                      -----  ----- *
*  SC       Solar constant                             J m-2 s-1 I    *
*  DAYL     Astronomical daylength (base = 0 degrees      h      I    *
*  SINLD    Seasonal offset of sine of solar height       -      I    *
*  COSLD    Amplitude of sine of solar height             -      I    *
*  DSINBE   Daily total of effective solar height         s      I    *
*  DTR      Daily total of global radiation             J/m2/d   I    *
*  RHO      Reflection coefficient of leaves for visible              *
*              radiation (PAR)                            -      I    *
*  AMAX     Assimilation rate at light saturation      kg CO2/   I    *
*                                                      ha leaf/h      *
*  EFF      Initial light use efficiency               kg CO2/J/ I    *
*                                                      ha/h m2 s      *
*  KDIF     Extinction coefficient for diffuse light             I    *
*  LAI      Leaf area index                              ha/ha   I    *
*  DTGA     Daily total gross assimilation           kg CO2/ha/d O    *
*                                                                     *
*                                                                     *
*  SUBROUTINES and FUNCTIONS called : ASSIM                           *
*                                                                     *
*  FILE usage : none                                                  *
*---------------------------------------------------------------------*

      SUBROUTINE TOTASS(SC,DAYL,SINLD,COSLD,DSINBE,DTR,RHO,AMAX,EFF,
     &KDIF,LAI,DTGA,FGROS,f1,f2,f3,RefH,RefDif,K15,K45,K75,
     &    DAY,LAISub,StemL,r,TideSw,AWL,ASWL,ANWL,HSWL,HNWL,
     &    BLevel,NPL)
      IMPLICIT NONE
      DOUBLE PRECISION SC,DAYL,SINLD,COSLD,DSINBE,DTR,RHO,AMAX,EFF,
     &KDIF,DTGA,FGROS,LAI,F1,F2,F3,RefDif,RefH,K15,K45,K75,
     &LAISub,StemL,r,TideSw,AWL,ASWL,ANWL,HSWL,HNWL,BLevel,NPL

      DOUBLE PRECISION XGAUSS(5), WGAUSS(5),PI,HOUR,SINB,PAR,FRDIF,
     &ATMTR,PARDIF,PARDIR

      INTEGER I, IGAUSS, DAY

      PARAMETER (PI=3.141592654)
      DATA IGAUSS /5/
      DATA XGAUSS /0.0469, 0.2308, 0.5000, 0.7692, 0.9531/
      DATA WGAUSS /0.1185, 0.2393, 0.2844, 0.2393, 0.1185/

C *---Assimilation set to zero and calculated on three different times
```

```
C     of the day (HOUR) and integrated with gaussian intergration
      DTGA = 0.
      DO 10 I=1,IGAUSS
      HOUR = 12.0+DAYL*0.5*XGAUSS(I)

C *---Sine of solar elevation
      SINB  = AMAX1(0.,SINLD+COSLD*COS(2.*PI*(HOUR+12.)/24.))

C *---Diffuse light fraction (FRDIF) from atmospheric transmission (ATMTR)
      PAR    = 0.5*DTR*SINB*(1.+0.4*SINB)/DSINBE
      ATMTR  = PAR/(0.5*SC*SINB)
      FRDIF  = 1.47-1.66*ATMTR
      IF (ATMTR.LE.0.35.AND.ATMTR.GT.0.22) FRDIF=1.-6.4*(ATMTR-0.22)**2
      IF (ATMTR.LE.0.22) FRDIF=1.
      FRDIF  = dMAX1(FRDIF,0.15+0.85*(1.-EXP(-0.1/SINB)))

C *---Diffuse PAR (PARDIF) and direct PAR (PARDIR)
      PAR    = 0.5*DTR*SINB*(1.+0.4*SINB)/DSINBE
      PARDIF = MIN(PAR,SINB*FRDIF*ATMTR*0.5*SC)
      PARDIR = PAR-PARDIF

      IF (TideSw.EQ.1) THEN
         CALL TIDE (HOUR,LAISub,StemL,r,AWL,ASWL,ANWL,HSWL,HNWL,
     &   BLevel,DAY,NPL)
        ELSE
         LAISub = 0
      END IF

      IF (LAISub.EQ.-999.) THEN
         FGROS = 0.
        ELSE
         CALL ASSIM (RHO,AMAX,EFF,KDIF,LAI,SINB,PARDIR,PARDIF,FGROS,F1,
     &   F2,F3,RefDif,RefH,K15,K45,K75,LAISub)
      END IF
C *---Integration of assimilation rate to a daily total (DTGA)
      DTGA = DTGA+FGROS*WGAUSS(I)

10    CONTINUE

      DTGA = DTGA*DAYL


      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE ASSIM                                                    *
*  Authors: Daniel van Kraalingen                                      *
*  Date   : 10-Dec-1987                                                *
*  Modified by Jan Goudriaan 5-Febr-1988                               *
*  Purpose: This subroutine performs a Gaussian integration over       *
*           depth of canopy by selecting three different LAI's and     *
*           computing assimilation at these LAI levels. The            *
*           integrated variable is FGROS. (See CABO-TPE report #?).    *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name    meaning                                    units  class     *
*  ----    -------                                    -----  -----     *
*  RHO     Reflection coefficient of leaves for visible                *
*             radiation (PAR)                           -       I      *
*  AMAX    Assimilation rate at light saturation      kg CO2/   I      *
*                                                   ha leaf/h          *
*  EFF     Initial light use efficiency             kg CO2/J/   I      *
*                                                   ha/h m2 s          *
*  KDIF    Extinction coefficient for diffuse light             I      *
*  LAI     Leaf area index                              ha/ha   I      *
*  SINB    Sine of solar height                           -     I      *
*  PARDIR  Instantaneous flux of direct radiation (PAR) W/m2    I      *
*  PARDIF  Instantaneous flux of diffuse radiation(PAR) W/m2    I      *
*  FGROS   Instantaneous assimilation rate of         kg CO2/   O      *
*          whole canopy                             ha soil/h          *
*                                                                      *
*  SUBROUTINES and FUNCTIONS called : none                             *
*                                                                      *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*

      SUBROUTINE ASSIM (RHO,AMAX,EFF,KDIF,LAI,SINB,PARDIR,PARDIF,
     &FGROS,F1,F2,F3,RefDif,RefH,K15,K45,K75,LAISub)
      IMPLICIT NONE
      DOUBLE PRECISION RHO,AMAX,EFF,KDIF,LAI,SINB,PARDIR,PARDIF,FGROS,
     &XGAUSS(5),WGAUSS(5),REFH,KDIRBL,KDIRT,
```

```
     &LAIC,VISDF,VIST,VISD,VISSHD,FGRSH,VISPP,FGRSUN,VISSUN,
     &FGRS,FSLLA,FGL,
     &O,O1,O2,O3,F1,F2,F3,RefDif,RefDir,K15,K45,K75,LAISub,
     &T2DS,SN,RangeT
      INTEGER I1, I2, IGAUSS


C *---Gauss weights for five point Gauss
      DATA IGAUSS /5/
      DATA XGAUSS /0.0469, 0.2308, 0.5000, 0.7692, 0.9531/
      DATA WGAUSS /0.1185, 0.2393, 0.2844, 0.2393, 0.1185/

C *---Calculation of average projection of leaves (O)
       O1 = AMAX1(0.26, 0.93*SinB)
       O2 = AMAX1(0.47, 0.68*SinB)
       O3 = 1 - 0.268*O1 - 0.732*O2
       O  = F1*O1 + F2*O2 + F3*O3
       T2DS   = F1*0.06 + F2*0.25 + F3*0.467 +
     &          SinB*SinB*(F1*0.81 + F2*0.25 - F3*0.4)
       RangeT = SQRT(12. * MAX(0.,T2DS - O*O))

C *---Extinction coefficient for direct radiation and total direct flux
       KDirBl = (O/SinB)
       KDirT  = KDirBl*SQRT(1-RHO**2)

C *---Reflection coefficient of direct radiation
       RefDir = RefH * 2 * O / (O + SinB)

C *---Extinction coefficient for diffuse radiation
       KDif=  (-LOG(0.178*EXP(-K15*(LAI-LAISub))
     &        + 0.514*EXP(-K45*(LAI-LAISub))
     &        + 0.308*EXP(-K75*(LAI-LAISub))))/(LAI-LAISub)

C *---Selection of depth of canopy, canopy assimilation is set to zero
       FGROS = 0.0
      DO 10 I1=1,IGAUSS
       LAIC = (LAI-LAISub)*XGAUSS(I1)

C *---Absorbed fluxes per unit leaf area: diffuse flux, total direct
C     flux, direct component of direct flux.
       VISDF = (1.-RefDif)*PARDIF*KDif*EXP(-KDif*LAIC)
       VIST  = (1.-RefDir)*PARDIR*KDirT*EXP(-KDirT*LAIC)
       VISD  = (1.-RHO)*PARDIR*KDirBl*EXP(-KDirBl*LAIC)

C *---Absorbed flux (J/M2 leaf/s) for shaded leaves and assimilation of
C     shaded leaves
       VISSHD = VISDF+VIST-VISD
       FGRSH  = AMAX*(1.-EXP(-VISSHD*EFF/AMAX))

C *---Direct flux absorbed by leaves perpendicular on direct beam and
C *   assimilation of sunlit leaf area by integrating over the sky
       VISPP  = (1.-RHO)*PARDIR/SINB
       FGRSUN = 0.
      DO 20 I2=1,IGAUSS
          SN = O + RangeT*(XGAUSS(I2)-0.5)
          VISSUN = VISSHD+VISPP*SN
          FGRS   = AMAX*(1.-EXP(-VISSUN*EFF/AMAX))
          FGRSUN = FGRSUN+FGRS*WGAUSS(I2)
20    CONTINUE

C *---Fraction sunlit leaf area (FSLLA) and local assimilation rate (FGL)
       FSLLA = EXP(-KDirBl*LAIC)
       FGL   = FSLLA*FGRSUN+(1.-FSLLA)*FGRSH

C *---Integration of local assimilation rate to canopy assimilation (FGROS)
       FGROS = FGROS+FGL*WGAUSS(I1)
10    CONTINUE
       FGROS = FGROS*(LAI-LAISub)

      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE TIDE                                                     *
*  Purpose: This subroutine calculates the water level of the Schelde*
*           based on a sinusoidal tide approach. This water level      *
*           determines the amount of LAI that is submerged (LAISub).  *
*                                                                      *
*----------------------------------------------------------------------*
      SUBROUTINE TIDE(HOUR,LAISub,StemL,r,AWL,ASWL,ANWL,HSWL,HNWL,
     &    BLevel,DAY,NPL)

      IMPLICIT NONE
```

```
 DOUBLE PRECISION HOUR,LAISub,TideTime,Level,AWL,ASWL,ANWL,
&HSWL,HNWL,BLevel,PI,StemL,r,s,r2,NPL,Aver,Ampl
 INTEGER DAY
 PARAMETER (PI = 3.141592654)

 TideTime=DAY*24+HOUR
 Aver = AWL + ((ASWL-ANWL)/2) * SIN(2*PI*TideTime/360.18)
 Ampl=  (((HSWL-ASWL)+(HNWL-ANWL))/2) +
&       (((HSWL-ASWL)-(HNWL-ANWL))/2) * SIN(2*PI*TideTime/360.18)

 Level= Aver + Ampl*SIN(2*PI*TideTime/12.42)
 IF (Level.LE.BLevel) THEN
     LAISub = 0.
   ELSE IF (Level.GE.(BLevel+StemL)) THEN
     LAISub = -999.
   ELSE IF ((Level.GT.BLevel) .AND. (Level.LT.(BLevel+StemL))) THEN
     r2 = r - ((Level - BLevel)/StemL)*r
     s = SQRT((Level-BLevel)**2 + (r - r2)**2)
     LAISub = 0.5 * NPL * (PI*s*(r+r2))
 END IF
 RETURN
 END
```

Appendix 2: Listing of parameters, variables, functions, and DATA-tables used in the bulrush growth model (BGMOD)

Name	Parameter/ Variable Function/ DATA-table	Value	Unit
AFGEN	Function	-	-
	An external function to perform a linear interpolation between two points. This function is mainly used to find intermediate values from a DATA-table		
AMAX	Variable	-	kg CO_2/ ha/ h
	Actual CO_2 assimilation rate at light saturation for individual leaves		
Ampl	Variable	-	m TAW
	Amplitude of the tide		
AMTMP	Variable	-	-
	Factor accounting for effect of daytime temperature (DDTMP) on potential CO_2 assimilation rate (AMX)		
AMTMPT	DATA-table	-	-
	DATA-table which holds the effect of temperature on CO_2 assimilation rate		
AMX	Parameter	50	kg CO_2/ ha/ h
	Potential CO_2 assimilation rate at light saturation for individual leaves		
ANWL	Parameter	3.01	m TAW
	Average Niep Water Level		
ASWL	Parameter	3.41	m TAW
	Average Spring Water Level		
ASRQ	Variable	-	kg DM/ kg CH_2O
	Coefficient to account for the conversion of CH_2O into DM		
ASSIM	Subroutine		
ASTRO	Subroutine		
ATMTR	Variable	-	-
	Atmospheric transmission coefficient		
Aver	Variable	-	m TAW
	Average water level		
AWL	Parameter	3.22	m TAW
	Average Water Level		
BLevel	Parameter	4.82	m TAW
	Elevation of the bulrush stand in the littoral zonation		
COSLD	Variable	-	-
	Intermediate variable to calculate solar declination		

Name	Parameter/ Variable Function/ DATA-table	Value	Unit

CVT Parameter 1.05 kg CH_2O/ kg DM
Factor which converts the translocated DM into CH_2O

D, D1, D2, D3 Variables - -
Intermediate variables to calculate RefDif

DAVTMP Variable - °C
Daily average temperature

DAY Variable - d
Number of days since start of calculation (usually 1 January)

DAYL Variable - h/ d
Day length

DDTMP Variable - °C
Average temperature during daytime

DS0 Variable - J/ m^2/ d not used in BGMOD
Daily extra-terrestrial radiation

DSINB Variable - s/ d
Integral of SINB over the day

DSINBE Variable - s/ d
As DSINB, but now corrected for lower atmospheric transmission at lower solar elevation

DTEFF Variable - °C
Daily effective temperature

DTGA Variable - kg CO_2/ ha/ d
Daily total gross assimilation of CO_2

DTMAX Variable - °C
The maximum daily temperature measured by KMI at Zele

DTMIN Variable - °C
The minimum daily temperature measured by KMI at Zele

DTR Variable - J/ m^2/ d
Total daily radiation at Munte measured by KMI

DVR Variable - 1/ d
Development rate of the crop

DVR0to1 DATA-table - 1/ d
DVR1to2 DATA-table - 1/ d
DVR2to3 DATA-table - 1/ d
DVR3to4 DATA-table - 1/ d
Tables holding development rates depending on DVS and daily average temperature

Name	Parameter/ Variable Function/ DATA-table	Value	Unit
DVS	State variable Development stage of the plant	-	-
EFF	Parameter Initial light use efficiency for individual leaves	0.45	(kg CO_2/ ha/ h)/ (J/ m^2/ s)
F1	Parameter Relative frequency of leaves in the 0-30° inclination class	0.05	-
F2	Parameter Relative frequency of leaves in the 30-60° inclination class	0.10	-
F3	Parameter Relative frequency of leaves in the 60-90° inclination class	0.85	-
FGL	Variable Assimilation rate at a certain depth in the canopy	-	kg CO_2/ ha/ h
FGROS	Variable Canopy assimilation rate on a certain point of time	-	kg CO_2/ ha/ h
FGRS	Variable Intermediate variable for FGRSUN, used in the integration over the sky	-	kg CO_2/ ha/ h
FGRSH	Variable Assimilation rate of shaded leaves	-	kg CO_2/ ha/ h
FGRSUN	Variable Assimilation rate of sunlit leaves	-	kg CO_2/ ha/ h
FRDIF	Variable Fraction diffuse radiation of total daily total radiation	-	-
FSLLA	Variable Fraction of sunlit leaf area	-	-
GPHOT	Variable Daily total gross assimilation of CH_2O	-	kg CH_2O/ ha/ d
HNWL	Parameter High Niep Water Level	4.79	m TAW
HOUR	Variable Hour during the day	-	h
HSWL	Parameter High Spring Water Level	5.53	m TAW
ILAI	Parameter Initial leaf area index	0	m^2/ m^2

Name	Parameter/ Variable Function/ DATA-table	Value	Unit
IRGRL	Parameter Rate of remobilixation	0.03841	cm^2/ cm^2/ °C/ d
IRhDead	Parameter Initial weight of dead rhizomes	0	kg DM/ ha
IRhLive	Parameter Initial weight of living rhizomes	5064	kg DM/ ha
IRoDead	Parameter Initial weight of dead roots	0	kg DM/ ha
IRoLive	Parameter Initial weight of living roots	279	kg DM/ ha
IStDead	Parameter Initial weight of dead stems	0	kg DM/ ha
IStLive	Parameter Initial weight of living stems	0	kg DM/ ha
K15, K45, K75	Variable Extinction coefficients for diffuse radiation originating from solar elevations of 15°, 45° and 75°	-	-
KDif	Variable Extinction coefficient for diffuse PAR radiation	-	-
KDirBl	Variable Extinction coefficient for black leaves	-	-
KDirT	Variable Extinction coefficient for total direct flux	-	-
LAI	Variable Leaf area index	-	m^2/ m^2
LAIC	Variable Cumulative leaf area index	-	m^2/ m^2
LAISub	Variable Submerged leaf area index	-	m^2/ m^2
LAT	Parameter Latitude of side	52	degrees
MAINT	Variable Maintenance respiration	-	kg CH_2O/ ha/ d
MAINTS	Variable Maintenance respiration at reference temperature	-	kg CH_2O/ ha/ d

Name	Parameter/ Variable Function/ DATA-table	Value	Unit
Ncomp	Parameter Number of compartments in the model	1	-
NPL	Parameter Number of stems per square meter	1185	stems/ m^2
O	Variable Average projection of the leaves into the direction of the solar beam	-	-
O1	Variable Projection of the 0-30° leaf-angle class	-	-
O2	Variable Projection of the 30-60° leaf-angle class	-	-
O3	Variable Projection of the 60-90° leaf-angle class	-	-
PAR	Variable Flux of photosynthetically active radiation	-	J/ m^2/ s
PARDIF	Variable Flux of diffuse photosynthetically active radiation	-	J/ m^2/ s
PARDIR	Variable Flux of direct photosynthetically active radiation	-	J/ m^2/ s
r	Variable Radius of stem just above the sediment	-	m
r2	Variable Radius of stem at water surface	-	m
RangT	Variable Intermediate variable used in the integration procedure of sunlit leaves	-	
RefDif	Variable Reflection coefficient for diffuse radiation	-	-
RefDir	Variable Reflection coefficient for direct radiation	-	-
RefH	Variable Reflection coefficient for horizontal leaves	-	-
Remob	Variable Remobilization rate	-	kg DM/ ha/ d
RemobFac	Parameter	0.422	-
RhDead	State variable Dead rhizomes	-	kg DM/ ha

Name	Parameter/ Variable Function/ DATA-table	Value	Unit
RhDeathRateTable	DATA-table Relative death rates of the rhizomes	-	-
RhDRate	Variable Death rate of the rhizomes	-	kg DM/ ha/ d
RhFr	Variable Fraction of TotGrow that goes to the rhizomes	-	-
RhFracTable	DATA-table Fractionating table for rhizomes	-	-
RhGrGrow	Variable Gross growth rate of the rhizomes	-	kg DM/ ha/ d
RhLive	State Variable Living rhizomes	-	kg DM/ ha
RhNetGrow	Variable Net growth rate of rhizomes	-	kg DM/ ha/ d
Rho	Parameter Reflection coefficient of individual leaves	-	-
RhRemob	Variable Amount of rhizomes that is available for remobilization	-	kg DM/ ha
RhTot	Variable Total weight of the rhizomes	-	kg DM/ ha
RoDead	State variable Weight of dead roots	-	kg DM/ ha
RoDeathRateTable	DATA-table Relative death rates of roots	-	-
RoDRate	Variable Death rate of roots	-	kg DM/ ha/ d
RoFr	Variable Fraction of TotGrow that goes to the roots	-	-
RoFracTable	DATA-table Fractionating table of roots	-	-
RoGrGrow	Variable Gross growth rate of roots	-	kg DM/ ha/ d
RoLive	State variable Weight of living roots	-	kg DM/ ha

Name	Parameter/ Variable Function/ DATA-table	Value	Unit
RoNetGrow	Variable Net growth rate of roots	-	kg DM/ ha/ d
RoTot	Variable Total weight of the roots	-	kg DM/ ha
s	Variable Slope of the conical shape of the stem	-	m
SC	Variable Solar constant	-	$J/m^2/s$
SINB	Variable Sine of solar elevation above the horizon	-	-
SINLD	Variable Intermediate variable in calculating solar inclination	-	-
SN	Variable Intermediate variable used in integration procedure of sunlit leaves	-	-
StDead	State Variable Weight of dead stems	-	kg DM/ ha
StDeathRateTable	DATA-table Relative death rates of stems	-	-
StDRate	Variable Death rate of stems	-	kg DM/ ha/ d
StemL	Variable Length of stem above the sediment	-	m
StemW	Variable DW of individual stem	-	g
StFr	Variable Fraction of TotGrow that goes to the stems	-	-
StFracTable	DATA-table Fractionating table of stems	-	-
StGrGrow	Variable Gross growth rate of stems	-	kg DM/ ha/ d
StLive	State Variable Weight of living stems	-	-
StNetGrow	Variable Net growth rate of stems	-	kg DM/ ha/ d

Name	Parameter/ Variable Function/ DATA-table	Value	Unit
StTot	Variable	-	kg DM/ ha
Total weight of stems			
T2DS	Variable	-	
Intermediate variable used in the integration procedure of sunlit leaves			
TBASE	Parameter	3	°C
Base temperature			
TEFF	Variable	-	°C
Effect of temperature on maintenance			
TideTime	Variable	-	h
Total time elapsed since start of calculation, used to calculate the water level of the Schelde			
TMAXT	Variable	-	°C
Daily maximum temperatures measured at Zele (Be)			
TMINT	Variable	-	°C
Daily minimum temperatures measured at Zele (Be)			
TMPSUM	Variable	-	°C
Temperature sum			
TOTASS	Subroutine		
TotDead	Variable	-	kg DM/ ha
Total weight of dead plant material			
TotGrow	Variable	-	kg DM/ ha/ d
Total daily DM growth rate			
TotLive	Variable	-	kg DM/ ha
Total weight of living plant material			
TotW	Variable	-	kg DM/ ha
Total weight of dead and living plant organs			
Trans	Variable	-	kg DM/ ha/ d
Translocation rate			
TransFac	Parameter	0.30	-
Amount of dying stems that becomes available for redistribution among the organ in TotGrow			
VISD	Variable	-	J/ m^2/ s
Absorbed flux of direct component of direct radiation per unit leaf area			
VISDF	Variable	-	J/ m^2/ s
Absorbed flux of diffuse PAR per unit leaf area			

Name	Parameter/ Variable Function/ DATA-table	Value	Unit
VISPP	Variable	-	J/ m^2/ s
	Absorbed flux of direct PAR per unit leaf area perpendicular on direct beam		
VISSHD	Variable	-	J/ m^2/ s
	Absorbed PAR by shaded leaves per unit leaf area		
VISSUN	Variable	-	J/ m^2/ s
	Absorbed PAR by sunlit leaves per unit leaf area		
VIST	Variable	-	J/ m^2/ s
	Absorbed total direct PAR per unit leaf area		

Appendix 3: Calculation of development rate tables

In BGMOD the phenological development of the plant is related to arbitrarily chosen development stages (DVS), see table 1. The development stage is calculated as the integral of the development rate (DVR), which depends on the development stage and the daily average temperature. The DVS at the current time determines the DVR-table from which the DVR is read, e.g. at DVS 2.32 the DVR2to3-table is used. The DVR is found by linear interpolation with daily average temperature. A DVR-table is based on the temperature sum (Tmpsum) elapsed between two development stages, this equals the sum of daily average temperatures minus base temperature (Tbase). The base temperature is a minimum temperature necessary for further development of the plant, if daily average temperature is below the base temperature the development rate equals zero. The base temperature differs between plants, in BGMOD the same value as in SUCREED was used, namely 3 °C.

	Date	Dayno.	Tmpsum	DVS
			(davtmp –tbase)	
Winter phase	1/1/97	0	0	0
Emergence	28/3/97	87	309.5	0.17
Flowering	1/8/97	212	1660.6	1
Start decay	1/9/97	243	2218.6	2
Fully senesced	1/10/97	273	2573	3
Post growth phase	31/12/97	365	3026	4

Table 1: DVS as used in BGMOD

Based on table 1 it is possible to find the DVR-tables from which a daily development rate can be found. The formula to calculate DVR0to1 is:

$$(25°C - Tbase) / (1660.6 - 0) = 0.0132$$

This means that with a daily average temperature of 25°C the development rate of that day equals 0.0132 [1/ d]. The graph for the total range of temperatures can be found in figure 1, it was assumed that development no longer increases after 25°C. This method was used to find the other necessary tables as well.

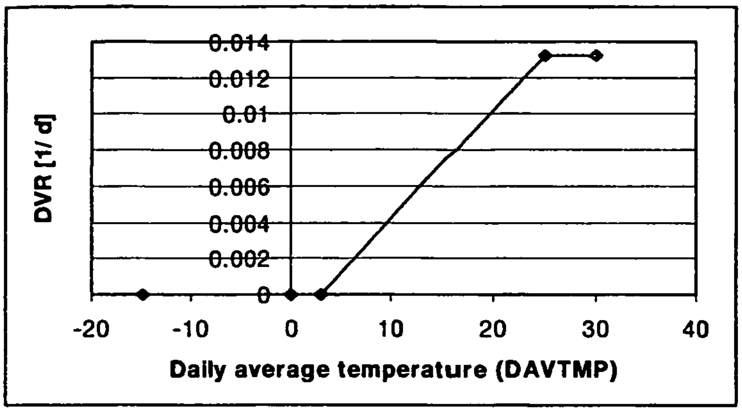

Figure 1: DVR as a function of daily averge temperature between stages 0 and 1

Appendix 4: Data of bulrush from Appels (Belgium)

Maurice Hoffmann of the Institute for Nature Conservation at Brussels, Belgium measured the aboveground DW of the stems at Appels (Belgium) used for calibration and validation. Mathieu Starink of the Netherlands Institute for Ecology - Centre for Estuarine and Coastal Ecology at Yerseke (the Netherlands) measured the DW of roots and rhizomes.

Aboveground DW development

The aboveground DW development was determined by weighing 75 dried stems every month in 1996 and 30 dried stems every two weeks in 1997. The stems were randomly chosen and clipped at the sediment. The sampling campaign started at June in 1996 and at April in 1997. Standard errors of the mean could not be calculated because only averaged weights were recorded, see figure 1 for averaged stem weights in 1996 and 1997.

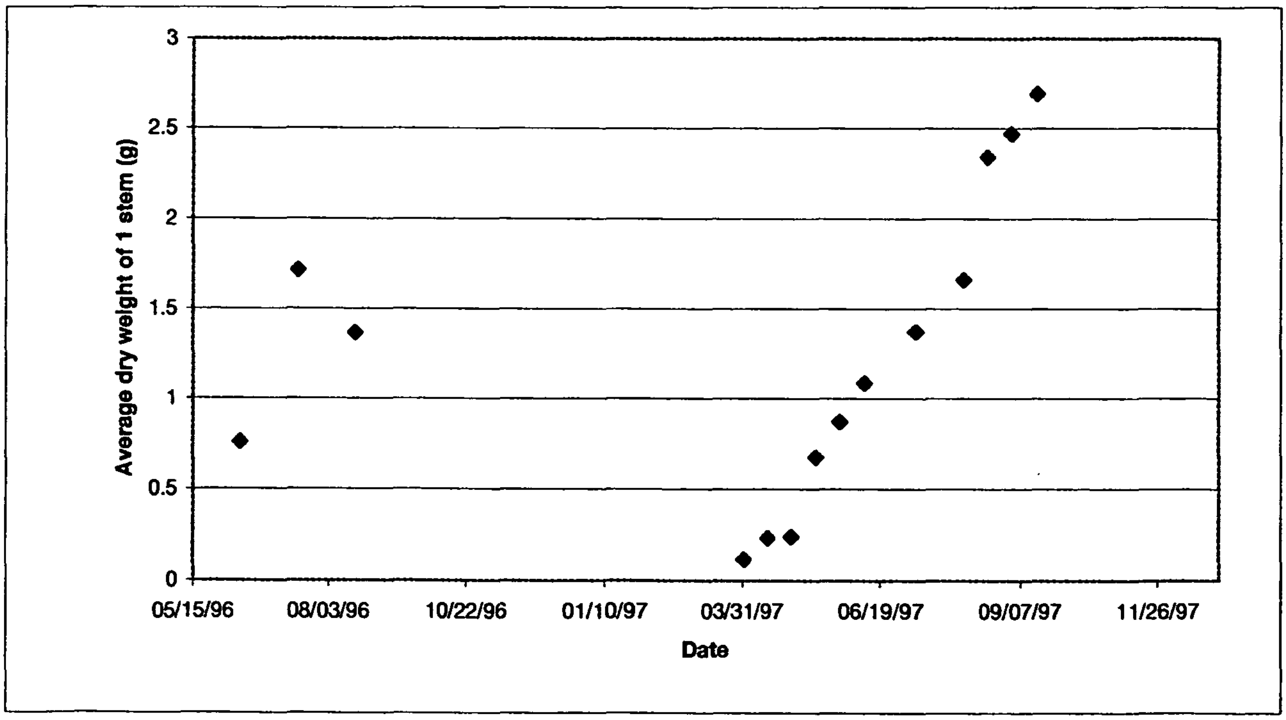

Figure 1: Averaged stem weights measured at Appels (Belgium) in 1996 and 1997

The model calculates the aboveground DW development in kg DM/ ha through the year. To transfer these from g DW/ stem to kg DM/ ha the number of stems per square meter was needed. Density measurements were not performed in 1996 and 1997. Therefore a density measurement took place at 22 April 1999. The number of stems per square meter was 1185 stems/ m^2. Next formula was used to transfer the data to kg DM/ ha:

$$\text{kg DM/ ha} = \text{g DM/ stem} * 1185 \text{ (stems/ } m^2\text{)} * 10$$

The resulting values were used to calibrate and validate the model.

Belowground DW development

At four times during 1996 belowground DW development was determined, in order to:

- Obtain data for calibration of the bulrush growth model;
- Find depth profiles of the roots. These depth profiles will be used as input for the diagenetic model (see figure 1.2), because the roots release oxygen to the sediment, which influences benthic microbial processes.

Every time 6 cores were sampled, the sediment from each core was cut into 5 cm slices till about 1 m depth. Every slice was analysed separately on roots and rhizomes. Because the sediment in the bulrush growth model is one-dimensional modelled, the data are averaged to DW per hectare. The weights of roots and rhizomes are presented in respectively figure 2 and 3. Due to the large spatial variability the standard errors of the mean are high, see table 1.

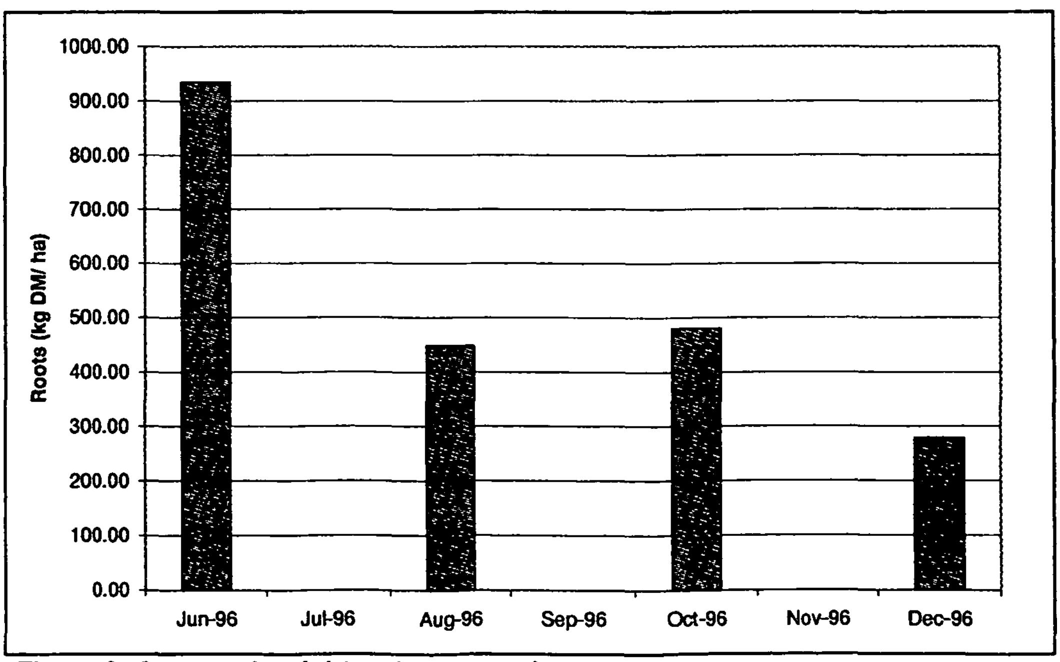

Figure 2: Averaged weights of roots per hectare

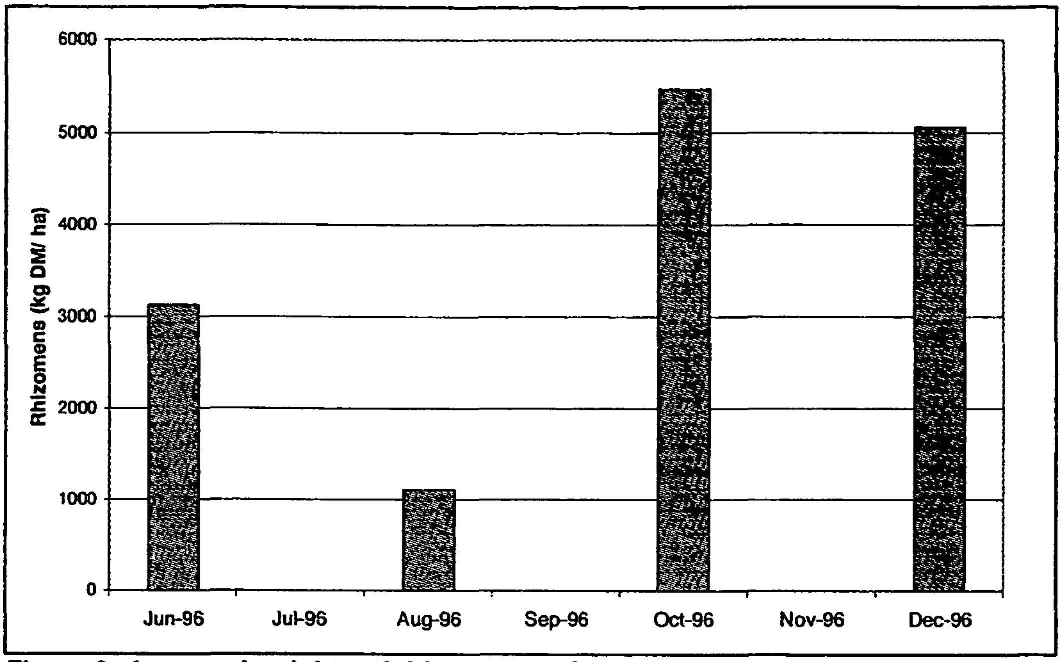

Figure 3: Averaged weights of rhizomes per hectare

	June '96	August '96	October '96	December '96
Roots	934.3 ± 216.8	448.7 ± 68.5	480.0 ± 154.1	279.1 ± 107.8
Rhizomes	3122.7 ± 1220.1	1108.8 ± 477.2	5475.4 ± 1862.2	5064.3 ± 2089.8

Table 1: Averaged weights of roots and rhizomes ± standard error

Appendix 5: Calculation of fractionating tables

In SUCREED the fractionating tables are determined by calculating the relative biomass increase of every organ, divided by the biomass increase of a specific organ with the total biomass increase. These results are used to set up the relative fractionating tables. This method can be used as long as the biomass of every organ increases through the year. However, in our study this is not the case and therefore this method was not used.

Table 1 gives an overview of the DW of the organs, the values in the cells are calculated using linear interpolation. The ratio of the DW of an organ and the total DW at a specific date is used to set up the fractionating tables (table 2).

	Stems	Roots	Rhizomes	Total
Date	kg DW/ ha			
01/01/97	-	-	-	-
31/05/97	-	-	-	-
06/12/97	13113	934	3123	17170
07/09/97	16294	2260	726	19280
08/14/97	24891	1109	449	26448
09/02/97	29270	2294	457	32021
10/23/97	0	5475	480	5955
12/12/97	0	5064	279	5343

Table 1: DW of plant organs in 1997

The first data on belowground biomass are from June 1996, therefore it was assumed that until the end of May 90% of the total growth rate is partitioned to the stems, 5% to the roots and another 5% to the rhizomes. This is a reasonable approximation because in springtime most of the total growth rate goes to the stems. The ratios on 12/12/97 are used till the end of the year (DVS of 3.99), because no DM has to be partitioned at that time of the year this doesn't influence the model.

	Dayno.	DVS	Stems	Roots	Rhizomes
01/01/97	0	0	0.9	0.05	0.05
31/05/97	151	0.48	0.9	0.05	0.05
06/12/97	162	0.59	0.7637	0.0544	0.1819
07/09/97	189	0.79	0.8451	0.0377	0.1172
08/14/97	225	1.42	0.9411	0.0170	0.0419
09/02/97	244	2.04	0.9141	0.0143	0.0716
10/23/97	295	3.45	0.0000	0.0806	0.9194
12/12/97	345	3.86	0.0000	0.0522	0.9478

Table 2: Fractionating tables as used in BGMOD

Appendix 6: Relations between stem weight and length/ thickness

In order to calculate the LAI based on the DM weight of a stem, relations between the weight and length/ thickness of the stems are needed. The data used to establish these relations are provided by Maurice Hoffmann (Institute for Nature Conservation, Brussels (Belgium)) and Jaco van der Nat (Netherlands Institute for Ecology - Centre for Estuarine and Coastal Ecology at Yerseke (the Netherlands)). The data of Maurice Hoffmann are obtained at Appels (Belgium) on 20/09/93, 15/09/95 and 22/08/96. The data obtained by Jaco van der Nat are from experiments under controlled climatic conditions. All available data on the relations between DM weight of a stem and length/ thickness are presented in respectively figure 1 and 2.

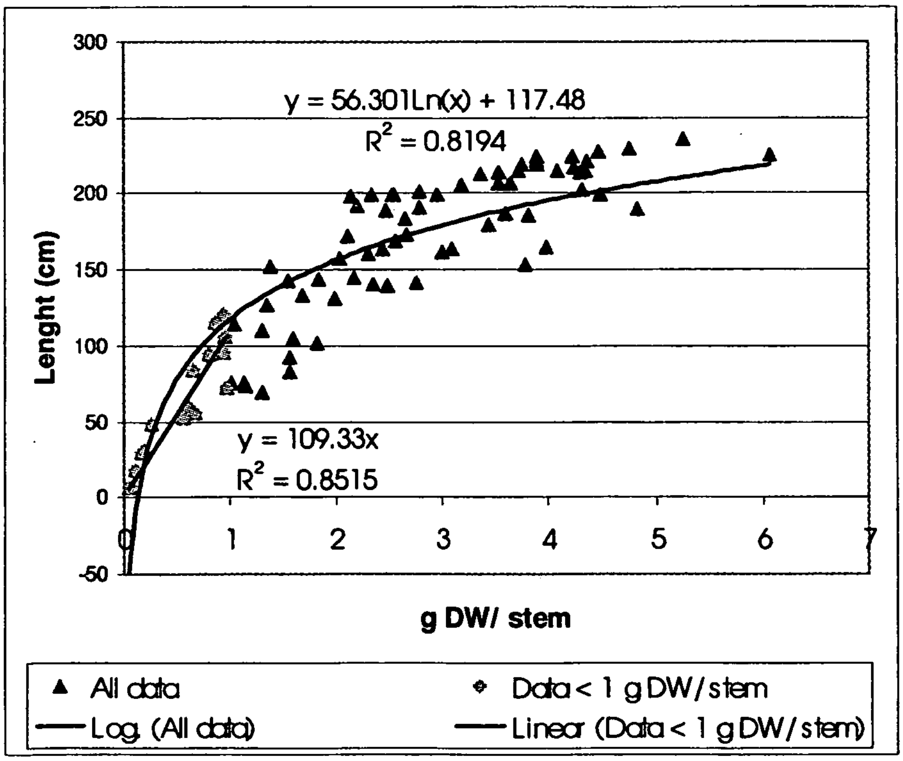

Figure 1: Relation between DW/ stem and length

Because for low DW values (< 0.16 gDW/ stem) the ln-relation between DW and length doesn't hold. Therefore a linear relation with low DW values (DW/ stem < 1 g) is set up. The relation between DW and thickness is good, only below a DW of 0.05 g/ stem this relation is valid to use, then a vast thickness of 0.5 mm is assumed. The model uses both approximations in the low DW range only during several days.

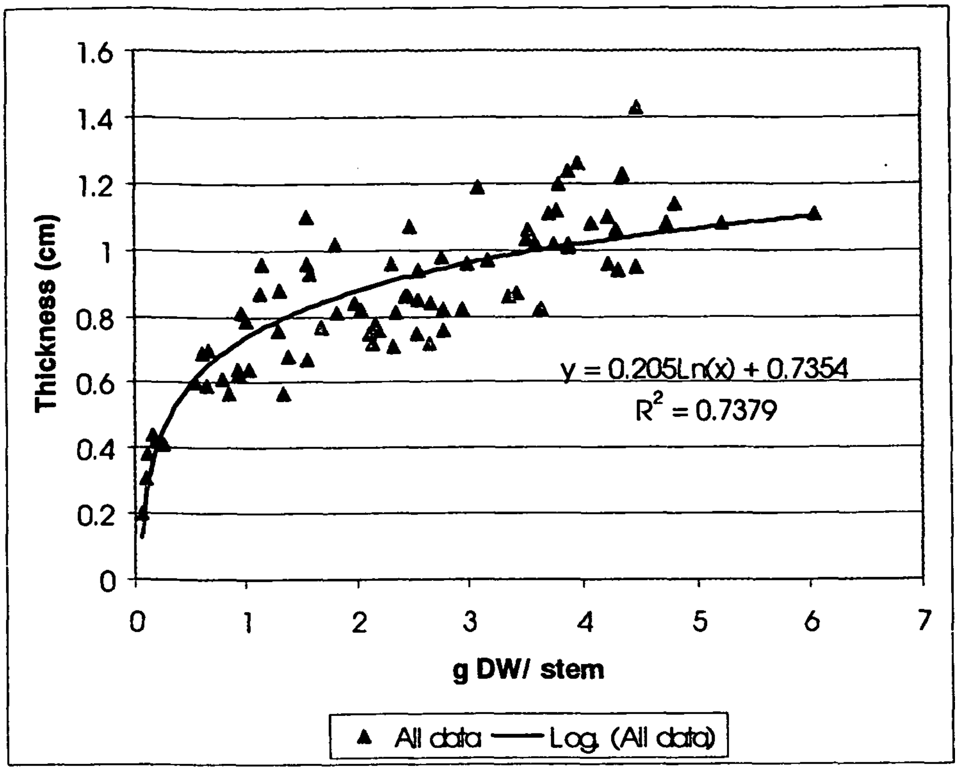

Figure 2: Relation between g DW/ stem and thickness

Appendix 7: Sinusoidal tide model of the Schelde

The tide on the Schelde can be approached with a sinusoidal model of the Schelde, for which data from table 1 can be used. These data are averaged water levels measured from 1981-1990 at Dendermonde (Belgium), this is the nearest point to Appels were water levels are recorded (Claessens & Meyvis, 1994).

	High water (m TAW)	Low water (m TAW)
Spring tide	5.53 (HSWL)	1.29 (LSWL)
Average tide	5.2 (AHWL	1.24 (AHWL)
Niep tide	4.78 (HNWL)	1.23 (LNWL)

Table 1: Average tide data at Dendermonde (Belgium)

The average water level varies sinusoidal with:

Aver = (AHWL + ALWL)/2 + (ASWL – ANWL)/2 * sin(2*Π*Time/360.18)

The amplitude varies sinusoidal:

Ampl = ((HSWL – ASWL) + (HNWL – ANWL))/2 +
((HSWL – ASWL) - (HNWL – ANWL))/2 * sin(2*Π*Time/360.18)

Combining both functions gives the sinusoidal tide approach:

Tide = Aver + Ampl * sin(2*Π*Time/12.42)

The result is graphically presented in figure 1.

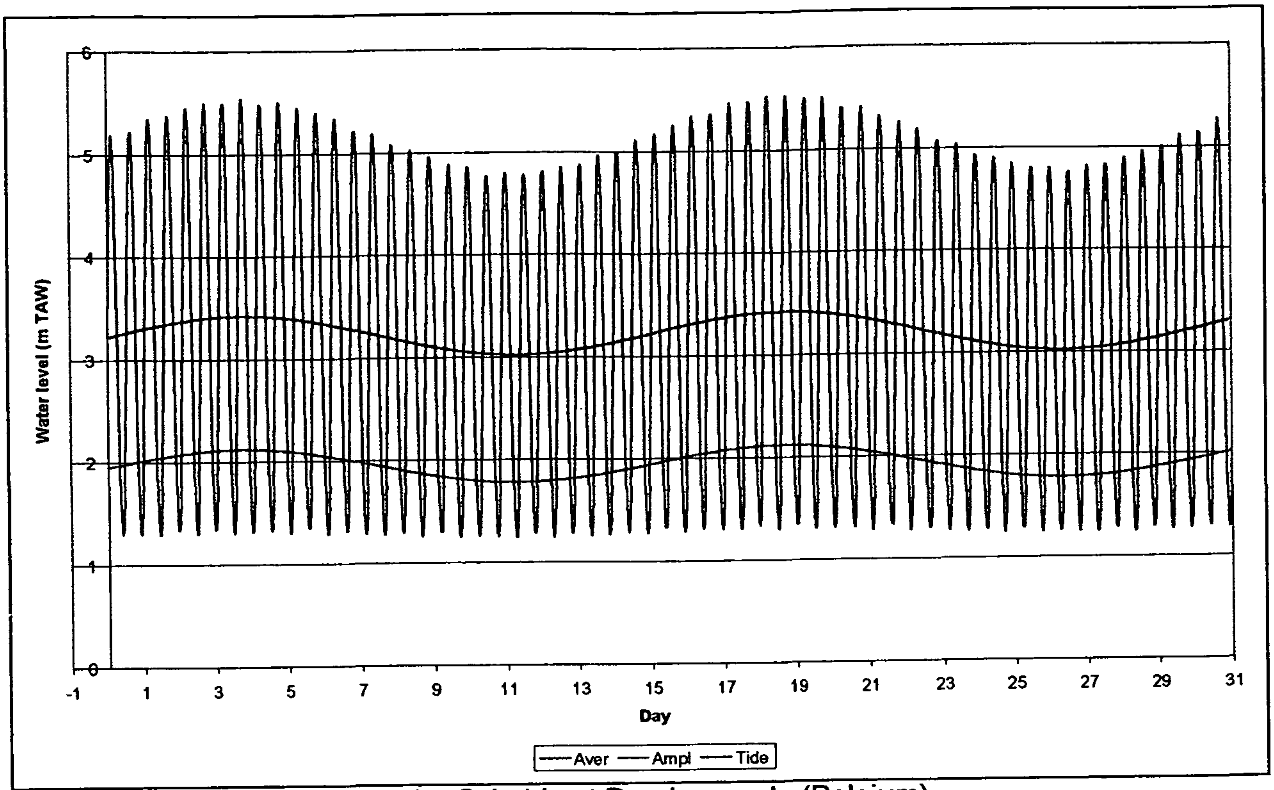

Figure 1: Sinusoidal model of the Schelde at Dendermonde (Belgium)