DOCTORAL THESIS

Study on stream water discharge and organic carbon concentrations, loads and yields of tropical peat swamp forest of Riau, Sumatra, Indonesia

DIVISION OF ENVIRONMENTAL RESOURCES

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Chapter 1
INTRODUCTION

1.1 Background

Tropical peatland represents approximately 4.41 x 10^5 km^2 (11% of the global peatland area), and 56% of tropical peatland area lies in Southeast Asia (approximately 2.48 x 10^5 km^2), particularly Indonesia and Malaysia (Page *et al*. 2011). Southeast Asia's peat deposits contain an estimate of 68.5 Gt C (77% of the total tropical Peat carbon (C), 88.6 Gt). This amount is equivalent to 11 to 14% of global peat C. The largest tropical peat C accumulation is in Indonesia (57.4 Gt, i.e. 65% of the total C in tropical peat), followed by Malaysia (9.1 Gt, 10%) (Page *et al*. 2011). Jaenicke *et al*. (2008) also estimate peat store of 55 ± 10 Gt C in Indonesian peatland. Tropical peatland is formed when organic matter accumulates as a peat layer. Peatland in tropical peat swamp forest (TPSF) has important roles in regulating water movement, the hydrological cycle (Dommain *et al*. 2010) as well as C storage (Limpens *et al*. 2008) in the regional and global C cycles. When affected by human activities, the organic C pool in peatlands can potentially release large amounts of organic C into the environment through air (gaseous) and waterborne (fluvial) losses (IPCC 2000).

Organic C is released from peatlands in substantial amounts (Page *et al*. 1999, Tachibana *et al*. 2006, Alkhatib *et al*. 2007, Baum *et al*. 2007, Rixen *et al*. 2008, Lähteenoja and Page 2011, Moore *et al*. 2011, Wright *et al*. 2011, Moore *et al*. 2013) and waterborne C may constitute a substantial part of the peatland C balance, as reported for boreal peatland (Roulet *et al*. 2007, Nilsson *et al*. 2008). Carbon is released into watercourses in both organic and inorganic forms

(Meybeck 1993) and also in gaseous form (free CO_2 and CH_4) (Dawson *et al.* 2004). Organic forms include of dissolved organic C (DOC) and particulate organic C (POC). It is well known that the water in tropical peatland rivers has very high DOC concentrations (Alkhatib *et al.* 2007, Miyamoto *et al.* 2009) and POC concentration is lower (Yoshioka *et al.* 2002).

Despite increasing interest in C release via TPSF river systems, few studies have been conducted. Baum *et al.* (2007) used data collected from the Siak River in Sumatra to calculate that *ca.* 0.3 Tg C yr^{-1} of DOC was released to Bengkalis Strait, whilst Moore *et al.* (2011) estimated from their own measurements in the Sebangau River in Central Kalimantan that 0.46 Tg C yr^{-1} of (total) organic C (TOC) was released to the Java Sea. These are valuable results, obtained by hard work in the field. However, to improve accuracy and to clarify how discharge variability influences the organic C load in TPSF watercourses, it is necessary to have continuous measurements of water discharge. This is because both rainfall events and discharge responses affect the rate of flow in stream and rivers. Periodic measurements of stream discharge combined with continuous recording of streamwater level (stage) can provide accurate continuous flow rate data if the rating curve (i.e. a graph of discharge versus stage is available (Bedient *et al.* 2008).

1.2 Objective

The purpose of this study was to know how much C release from TPSF stream water. Furthermore the C loads of watercourses draining from selected area of TPSF in Riau Province, Sumatra, Indonesia were quantified, by combining continuous flow data with measurements of organic C concentration in the water; thus to estimates catchment yields of organic C. We also compare results obtained using continuous measurements of organic C load with those that would be indicated by periodic measurements. From this study also can give contribution and adding the information related C dynamics in TPSF streamwater.

Chapter 2

LITERATURE REVIEW

2.1 Tropical peatlands

Tropical peatlands, which coexist with the tropical peat swamp forest (TPSF) is one of a unique ecosystem of tropics, and it one of large C sinks for long-term period that became the largest repositories of terrestrial organic C playing an important role in the global C cycle (Page *et al*. 2011).

In a natural state, TPSF are characterized by dense forest vegetation, in particular they contain a large number of endemic tree species, which have significant commercial value. Varieties of the trees depend on TPSF types shown in Figure 2.1. The trees of TPSF have often extensive supportive root systems with buttress or stilt roots as well as air conducting pneumatophores as adaptations to wet environment (http://blogs.helsinki.fi/jyjauhia/peat-swamp-forests/).

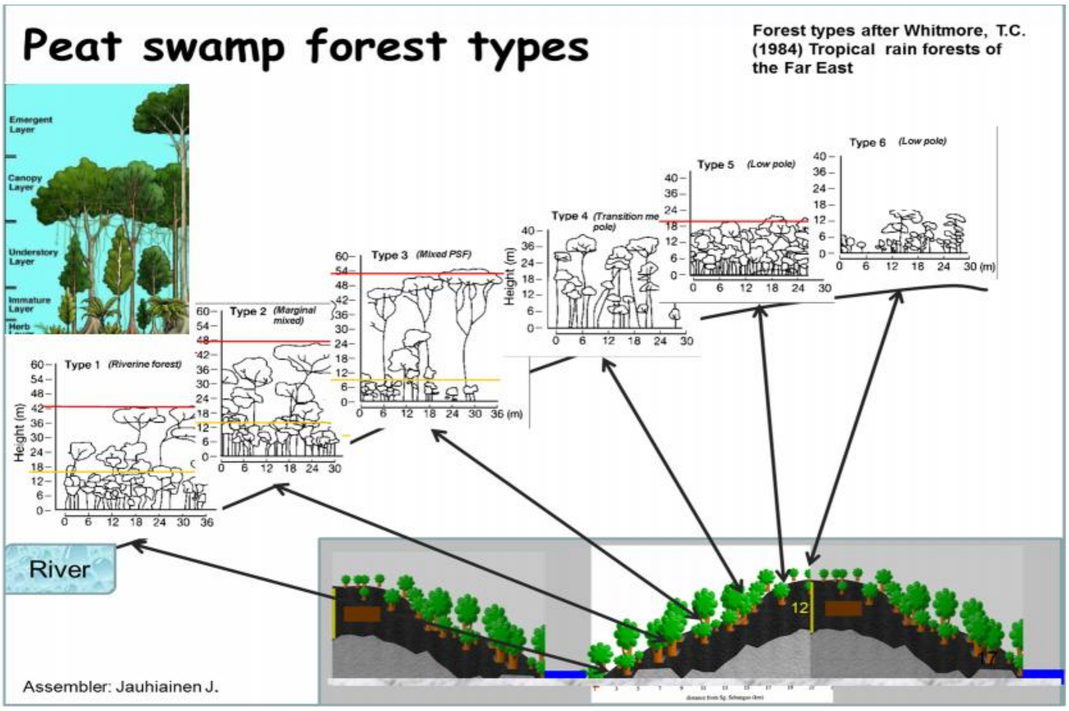


Figure 2.1. Outline of peat swamps forest types (after Whitmore, 1984).

TPSF have been recognized as important reservoirs of biodiversity, as refugees for several rare and endangered animals, including orang-utan, while streams and rivers draining from peatlands are important for fish habitats (http://blogs.helsinki.fi/jyjauhia/peat-swamp-forests/). TPSF also have an important hydraulic function in storing excess rainfall (water reservoir) thus can control water movement for the catchment scale on wet and dry condition (Wösten *et al*. 2006, Dommain *et al*. 2010). As the buffer zone, TPSF also can protect the coastal and inland area from windstorm, erosion prevention and flood mitigation (Rieley and Page, 2005).

Indonesia has the largest area of peat swamp forest in the tropics, covering an estimated 20.7 Mha (range 16–27 Mha) (Sorensen, 1993, Rieley *et al*. 1996, Page *et al*. 2011) and distributed mainly across Sumatra (4.7–9.7 Mha), Kalimantan (3.1–6.3 Mha) and Irian Jaya (8.9 Mha) (Silvius, 1989, Rieley *et al*. 1996). In Central Kalimantan, around 3 Mha or 20% of the area is peatland (Hooijer *et al*. 2006) and most of this remained pristine up to the beginning of the 1990s (Siegert *et al*. 2001) Figure 2.2.

TPSF are rain water fed ecosystems, and thus the nutrient input to this ecosystem comes only from rain water and trough dry deposition from the atmosphere. The concentrations of nutrients in peat profile under the upmost surface peat remain very low. Excess amount of water in the forest floor causes intermittent lack of oxygen that inhibits the litter decomposition and thus creates favorable conditions for accumulation of organic matter, i.e., peat. Peat C accumulates as a result of a positive net imbalance between high tropical ecosystem primary production and incomplete organic matter decomposition in permanently saturated soil conditions (Hooijer *et al*. 2010, Wösten *et al*. 2008).

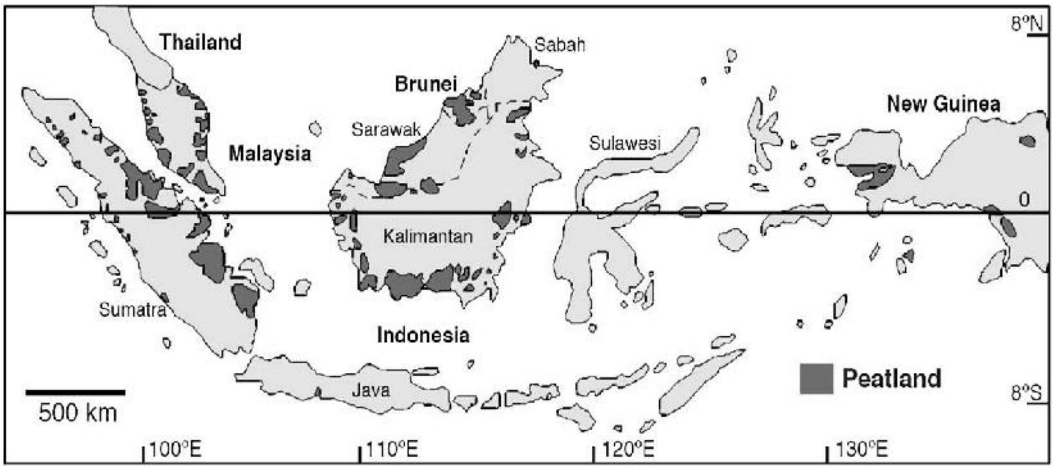


Figure 2.2. Map of Peatlands distribution in the Southeast Asia (after Page *et al*., 2004)

Tropical peatlands contain a large amount of organic C and nitrogen (N) under waterlogged conditions and could, therefore, be important sources of CO_2, CH_4, N_2O (Bouwman, 1990, Kasimir-Klemedtsson *et al*. 1997, Mosier *et al*. 1998). From peatland also was released through the streamwater (C leaching) as dissolved organic C (DOC) or particulate organic C (POC) as well as gaseous form i.e., C-CO_2 and C-CH_4 (Dawson et al. 2004).

2.1.1 Tropical peatland characteristics.

Tropical peatlands is very different from boreal and temperate peatlands. In the temperate and boreal zones, peat is derived mainly from grasses, sedges and sphagnum moss. Whereas, tropical peatland has rather heterogenic physical structure; remains of wood in varying size and degree of decomposition are often mixed with well decomposed substrate. Biomass forming solely of trees thus the peat is woody (http://blogs.helsinki.fi/jyjauhia/peat-swamp-forests/) so that peat contains large amounts of organic matter, generally acidic and poor-nutrient (Page *et al*. 1999 and 2004, Wösten *et al*. 2008, Jauhiainen *et al*. 2010). Tropical peatland have formed under a high rainfall-high temperature climatic regime. An important consequence of high temperature is that peat degradation proceeds rapidly when there is a change in the peatland ecosystems and its water regime, either as a result of natural climatic change (reduced rainfall or extended dry season) or human-induced ones (for example, on- and off-site drainage and fire) (Page *et al*. 2009). They are waterlogged throughout the year under natural conditions (Ritzema, 2007). Tropical peat has a higher hydraulic conductivity, especially in the upper layer. This is a result of the larger, more open structure due to the hemic and fibric remains of rain forest trees (Silvius *et al*. 1984). The hydraulic conductivity of tropical peat is typically more than 10 mm d^{-1}, whereas for boreal Sphagnum bog it is only around 0.01 mm d^{-1} (Takahashi and Yonetani, 1997). The bulk density is around 0.1 g cm^{-3} in the more decomposed hemic topsoil and lower in the less decomposed fibric subsoil (Wösten and Ritzema, 2001).

Although the water balance of tropical peat dome may seem rather simple, since it can be expressed in just 4 terms (rainfall, evapotranspiration, storage and runoff), its hydrology is complex (Ritzema, 2007). In undrained PSF, water movement mainly takes place in the wet season (Takahashi *et al*. 2002). Deep percolation is rather low as more than 90% of the excess rainfall runs through the top peat layer so called in term of “interflow” (Department of Irrigation and Drainage, Sarawak 2001). Owing to the convex character of tropical peat dome, this water flows in various directions as radial, widely spread sheet flow rather than channel flow.

Tropical peat ages for some area have been obtained. It depend on the type of peat and location. Mostly the peat in the tropics are less than 10,000 years old (Andriesse, 1988). Brady (1997) revealed that much of the coastal peat in Sumatra began its accumulating between 4,000 and 4,500 BP. Staub and Esterle (1994) found that basal peat in Sarawak has been dated to about 7,000 BP, while ombrogenous peat at the sediment-peat interface at the depth of 8.4 m of Kalimantan, started its accumulate about 22,120 BP (Weiss *et al*. 2002).

2.1.2 Topography

From aspects of landscape; the topographical classification systems are principal importance. The hydrological conditions, the origin of the peat swamps, the nature of the accumulated material are all related to topography. So that topographical classifications are useful for indicating possible limitation on reclamation and necessary management procedures (Andriesse, 1988).

According to Andriesse (1988) the topography situation characterizes the position of the peatswamps in relation to surrounding landscapes they consists of;

- Deltaic peatswamps, coastal basin peatswamps, lagoonal peatswamps, small inland valley peatswamps, major valley peatswamps, meander bend peatswamps, isolated small bottomland peatswamps and atoll peatswamps.

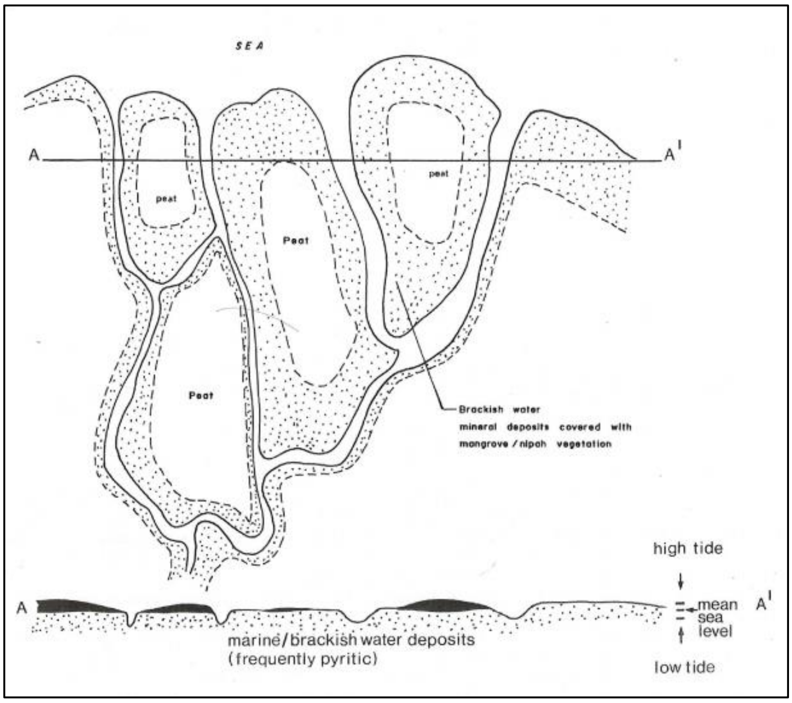


Figure 2.3. Deltaic dome-shaped peatswamps (after Andriesse, 1988)

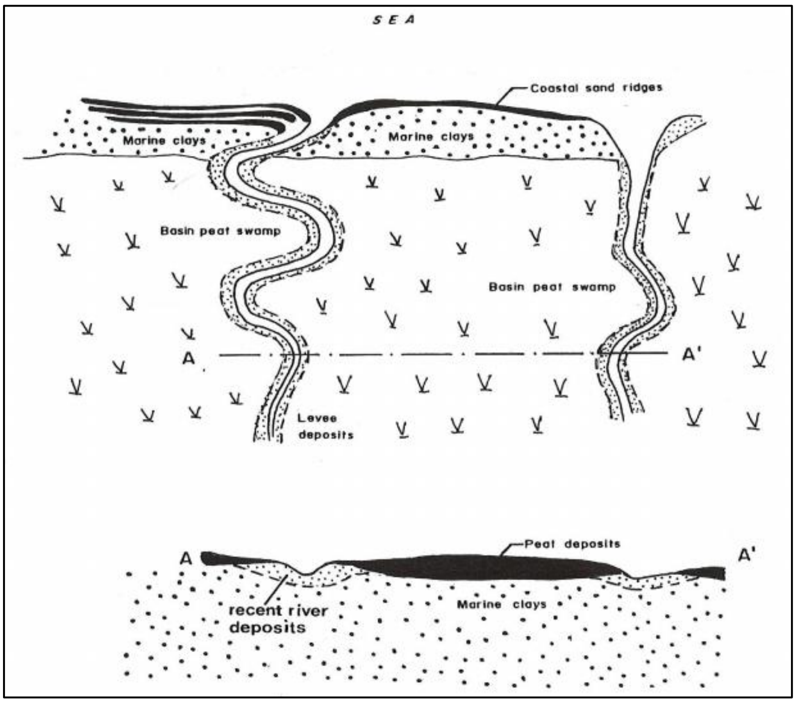


Figure 2.4. Coastal dome-shaped basin peatswamps (after Andriesse, 1988)

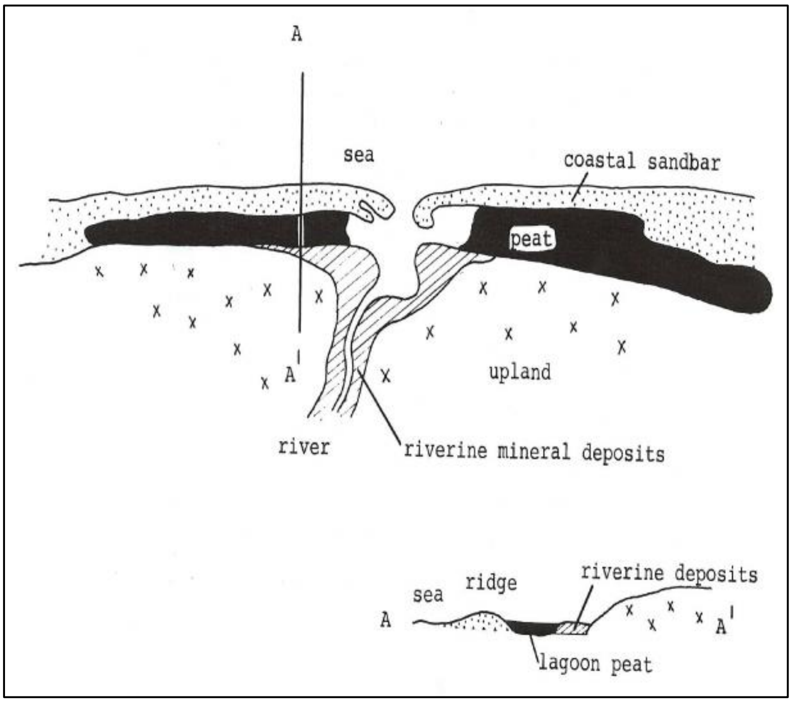


Figure 2.5. Lagoonal peatswamps (after Andriesse, 1988)

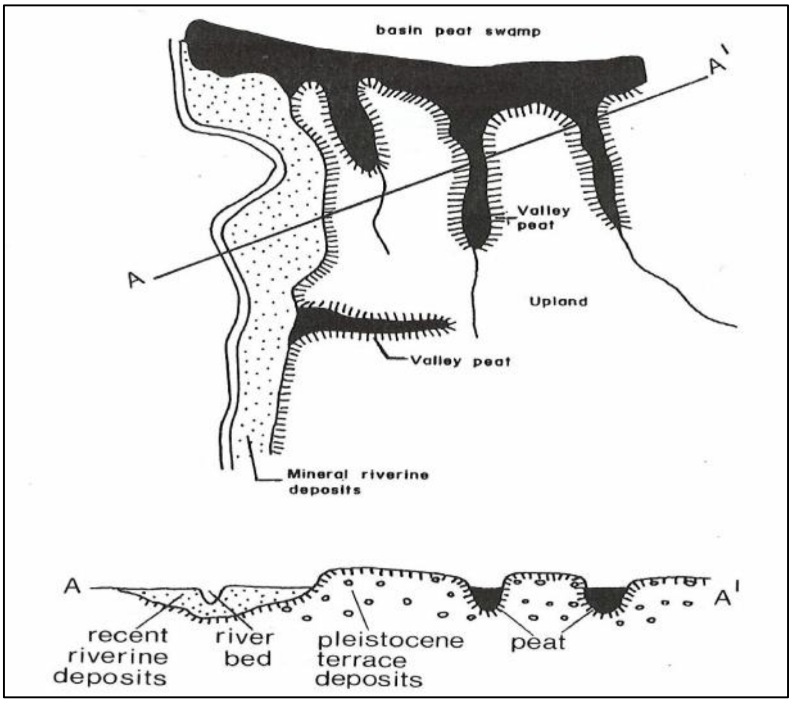


Figure 2.6. Small inland valley peatswamps merging into basin swamps (coastal position) (after Andriesse, 1988)

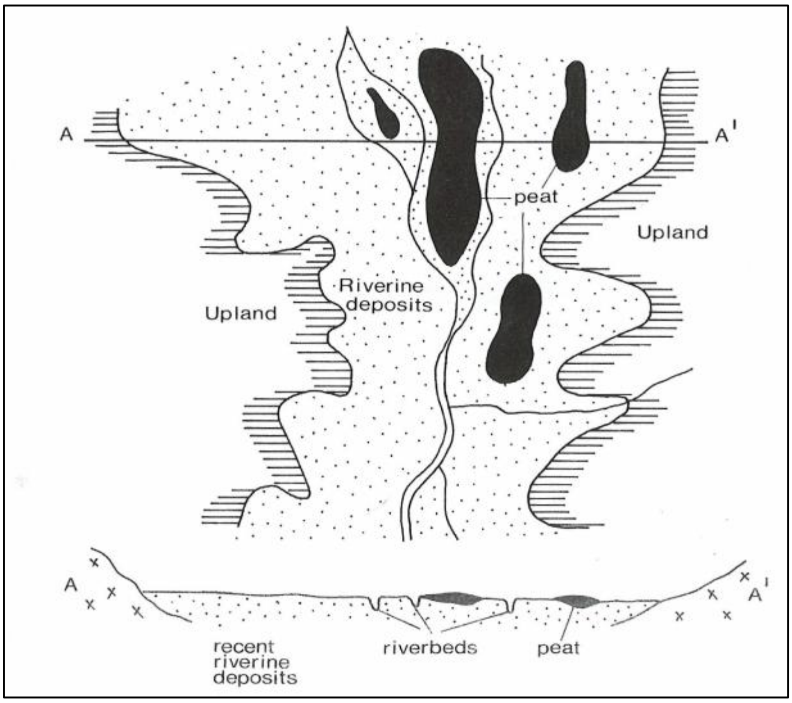


Figure 2.7. Isolated peatswamps in major valleys (after Andriesse, 1988)

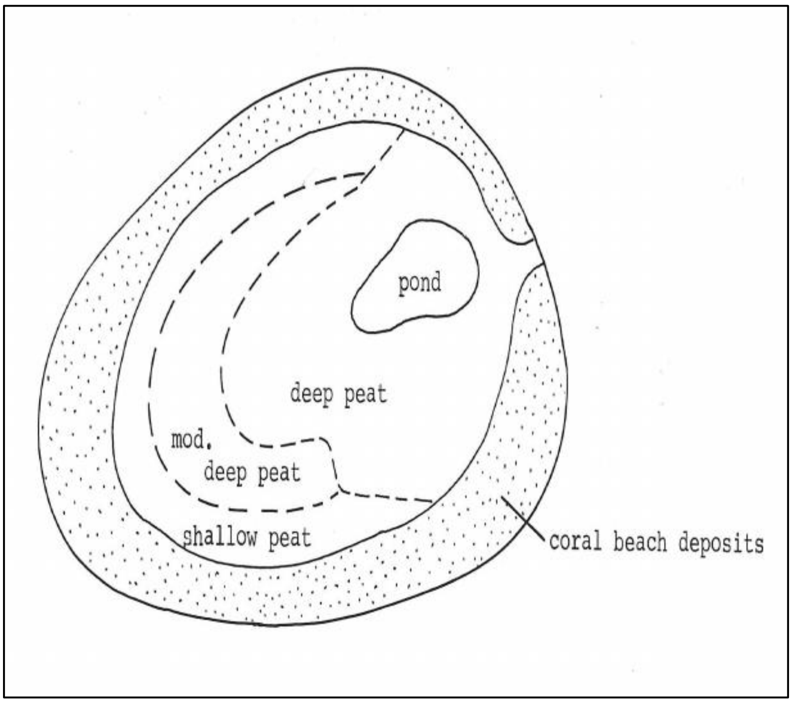


Figure 2.8. Atoll peat deposits (partly saline) (after Andriesse, 1988)

In tropical peatswamps area such as Indonesia, the peatswamps forest positions are mainly characterizes as deltaic and coastal basin peatswamps, lagoonal peatswamps and also small inland valley peatswamps. Many peatswamps in the tropics have a dome-shaped surface (Andriesse, 1988). Rieley *et al*. (1996) stated that coastal peatlands are situated in sub-coastal and deltaic areas where their formation has been affected by fresh or brackish water overlying marine sediments. In contrast, basin or valley peatlands arise inland along river valleys at slightly higher altitudes compared to coastal peatlands. The high peatlands are located in higher altitude watershed positions between major river systems, overlying podzols and fine alluvial clays.

In forested peat areas the aerial roots of many swamp trees form stilts and also form as buttress which can be more than 50 cm higher than surrounding land surface. The buttress root could create and change the peatland surface by forming the new hummock and hollow Figure 2.9. Whatever its origin, microtopography, of peat surface makes it difficult to level the land accurately (Andriesse, 1988).

Figure 2.9 Tropical peatswamps forest floor with the buttress root (private doc. 2013).

2.1.3 Hydrology

Hydrology, i.e., water occurrence (rainfall), water distribution and movement is vital of peat swamps ecosystem. It could influences chemical and biological processes and regulation (Mitsch and Gosselink, 1993). The main influence starts with the process of peat formation, and is followed by other hydrochemical processes as highlighted by Ross (1999) as (a) solute chemical and biochemical transformation, (b) solute storage and retention processes, and (c) solute transport processes. In addition, hydrology influences peatland formation by regulating interactions between vegetation, nutrient dynamics and carbon fluxes (Waddington and Roulet, 1997).

Peatswamps have an important role as controlling function on the hydrology of entire catchment, i.e. peat act as water reservoir as well as water regulator (Dommain *et al*. 2010). Natural lowland tropical peat swamps absorb and store water during wet periods when rainfall is heavy and release water gradually in dry periods when the rainfall is low (Prentice, 1990, Rieley *et al*. 1992, Page and Rieley, 1998). By their role in retaining and storing water, natural peat swamps landscapes can reduce the risk of flooding and drought.

2.1.3.1 Rainfall and TOC

The amount of rainfall that falls on a site has considerable influence on the concentration of Total Organic Carbon (TOC) that is measured within a catchment. The movement of TOC from the soil to water bodies or stream is primarily controlled by water movement which derives from rainfall.

2.1.3.2 Water movement and its influences of TOC

In tropical peatland, the rainfall water will infiltrate into peat soil and subsequently percolates via groundwater in saturated condition (Ward and Robinson, 1990) as subsurface flow. Then eventually can reach streamwater (water bodies), to produce the base flow within the stream. Water movement in peat soil as the interflow mainly occurred in wet season (Takahashi *et al*. 2002). During periods of dry season this base flow primarily controls the carbon concentration that is measured in the stream.

Water flow over the surface of the land (surface flow) also reaches to the streamwater. Surface flow will occur if the rainfall falls at a greater rate than the soils infiltration capacity. The excess amount of rain will flow over the ground as overland flow.

Water movement via a range of hydrological pathways (surface flow and subsurface flow) can transport TOC from peatland to the streamwater. The hydrological pathways will determine the concentration of TOC of water that is measured, as the available concentration of TOC alters with soil horizon, where higher concentrations would be available in the litter layers and upper organic horizons (McDowell and Likens, 1988, Hongve, 1999) than the mineral horizons (Easthouse *et al*. 1992, Kalbitz *et al*. 2000, Moore *et al*. 1992).

Schreiber and Duffy (1982) found that between 33 to 77% of TOC was transported from the soil to the stream system during high rainfall. A strong relationship has also been identified between dissolved organic carbon (DOC) concentrations and the discharge in a range of catchments (Grieve, 1984, McDowell and Wood, 1984, Worrall *et al*. 2002).

2.1.3.3 Evapotranspiration

The main water loss from peat ecosystems is through evaporation. According to Ingram (1983), a large proportion of the water recharge which peat receives is subsequently discharged by evaporation. Evaporation includes three main processes: interception, transpiration and evaporation. The rates of evapotranspiration (ET) from peat swamps depend on the vegetation types, even within one type of peat and this is especially clear where trees are present. On the other hand, ET also depends on various climate factors: solar radiation, temperature, air humidity, and wind velocity.

ET is markedly higher from peatland compared to mineral soils in agricultural or forestry use (Eggelsmann, *et al*. 1993). Annual ET from humid tropical forest ranges from 1,310 to 1,500 mm (Bruijnzeel, 1990). Takahashi and Yonetani, (1997) quantified the daily rates of ET for the peat swamp area in Central Kalimantan varies between 2.6 and 3.0 mm per day. Whereas Hirano *et al*. (2014) quantifying the annual ET in TPSF of Central Kalimantan-Indonesia is 67% of annual rainfall (P: 2446 mm) that is equals to 4.5 mm per day. In Malaysia, annual ET is reported to 72% of annual rainfall (P: 1545 mm) (Kumagai *et al*. 2005).

2.2 Carbon cycle

Carbon provides the basic building blocks for all life on earth, and the natural carbon cycle shown in Figure 2.10 is one of the most important material cycles of the globe. The principal fluxes of carbon in the natural carbon cycle, are between the atmosphere and ocean (90 P g C yr^{-1}), and the atmosphere and land

(120 Pg C yr^{-1}), which are approximately balanced each year (Intergovernmental Panel on Climate Change (IPCC), 2001).

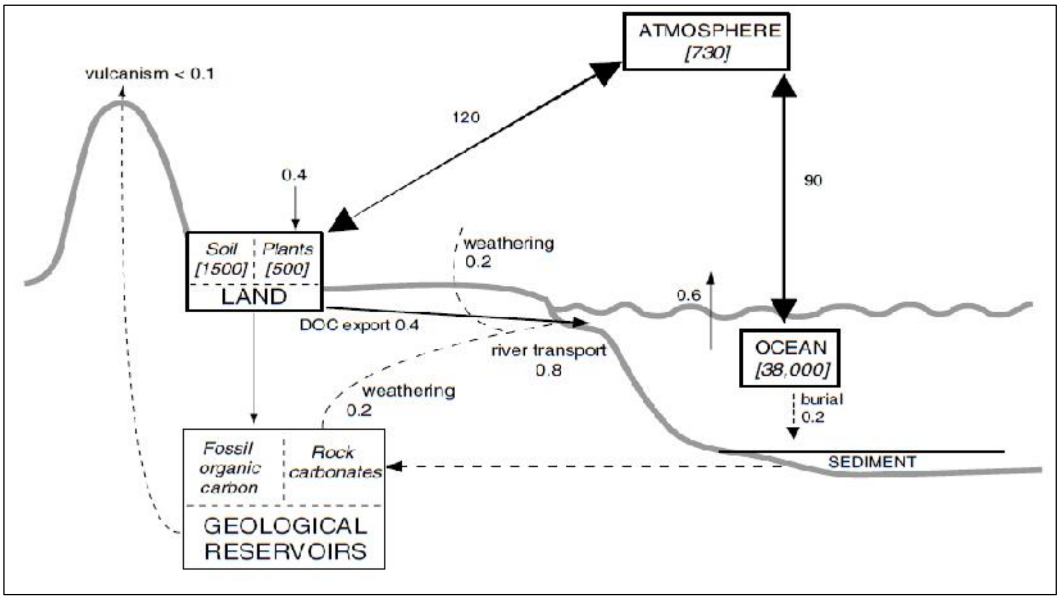


Figure 2.10. The main components of the natural global carbon cycle: The thick arrows show the gross primary production and respiration by the land biomass and the physical exchange between the air and sea. The thin arrows represent additional natural fluxes, with the dashed thin line denoting the fluxes of $CaCO_3$. All the fluxes shown are measured in PgC/yr (after Intergovernmental Panel on Climate Change (IPCC), 2001).

2.2.1 The role of soil and plants on carbon cycle

The land stores 2000 Pg C, which is split between the soil and plants. 500 Pg C is stored by plants, which assimilate 120 Pg C yr^{-1} from the atmosphere for use in photosynthesis (IPCC, 2001). This CO_2 flux is returned to the atmosphere via respiration by plants (60 Pg C yr^{-1}), heterotrophic respiration (55 Pg C yr^{-1}), and direct oxidation in fires (4 Pg C yr^{-1}) (IPCC, 2001). The soil is a large sink for carbon, storing perhaps two or three times more carbon than is found in the atmosphere as CO_2 (Davidson *et al*. 2000). The estimates of this organic carbon store, in the top 100 cm of soil, have ranged from 1395 Pg (Post *et al*. 1982) to more recent estimates of 1462–1548 Pg (Batjes, 1996) and 1500 Pg by the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change (IPCC, 2001). The carbon that contributes to this large but active soil store initially joins the detritus pool, where it either quickly decomposes and is respired by heterotrophs, or is converted to modified soil carbon (humus) which takes longer to decompose and respire. A further small fraction of the modified soil carbon is resistant to decomposition; this along with the black carbon produced in fires makes up the inert carbon pool (IPCC, 2001). A major soil store of carbon is peat, accumulating as a result of the slow decomposition processes that occur within peat (Grieve and Marsden, 2001). The large sink of carbon found within peatlands, represents a large potential source of (DOC). It has been estimated that within the top 100 cm, there are 330 Pg of carbon in peat (Batjes, 1996).

2.2.2 Human activity on carbon cycle

The natural carbon cycle has however been detrimentally altered by human activity through increasing emissions of CO_2 from the burning of fossil fuels (5.3 $PgCyr^{-1}$), cement production (0.1 $PgCyr^{-1}$) and land use change (1.7 $PgCyr^{-1}$), all contributing to the increase of CO_2 concentrations measured within the atmosphere (IPCC, 2001). Indeed, changes in land use have been identified to have contributed a net flux of 124 PgC to the atmosphere for 140 years between 1850 and 1990 (Houghton, 1999). The flows to the atmosphere are primarily from forests as a result of wood harvesting (108 PgC) and from the conversion of forests to agricultural lands (105 PgC). Other factors contribute to a smaller extent to this flux, which totals 337 PgC. This figure is then balanced with the carbon that accumulates within the forest and the fallows of shifting cultivation (249 PgC) to produce the net flux of 124 PgC (Houghton, 1999). Anthropogenic disturbance of catchment, often specific to vegetation type, and also can alter organic carbon concentrations.

2.2.3 Specific form of carbon (C) in the stream and river network

Through the stream and river networks within the watershed, many substances including of carbon (C) were continuing transport from the land to the ocean. Stream or riverine C may be classed as dissolved or particulate. Total amount of dissolved inorganic and organic C as well as total amount of particulate inorganic and organic C were defines as total C (Meybeck, 1993) and also in gaseous form i.e., C-CO_2 and C-CH_4 (Dawson et al. 2004). In Table 2.1 the specific form of carbon in stream and river has shown.

Table 2.1 Specific form of carbon (C) in stream and river

<table>
<tr><th colspan="3">Major-specific form</th></tr>
<tr><td rowspan="6">Carbon (C) species</td><td rowspan="2">Dissolved carbon</td><td>DIC
(dissolved inorganic carbon)</td></tr>
<tr><td>DOC
(dissolved organic carbon)</td></tr>
<tr><td rowspan="2">Particulate carbon</td><td>POC
(particulate organic carbon)</td></tr>
<tr><td>PIC
(particulate inorganic carbon)</td></tr>
<tr><td rowspan="2">Gaseous carbon</td><td>C-CO_2</td></tr>
<tr><td>C-CH_4</td></tr>
</table>

Dissolved organic C (DOC), dissolved inorganic C (DIC) and particulate organic and inorganic C (POC, PIC) are rather small, yet important components of the global carbon cycle. The export of DOC from soils and plants to rivers and oceans, accounts for a load of 0.4 $PgCyr^{-1}$, which is subsequently respired and released to the atmosphere (IPCC, 2001).

DIC is produced within the soil, through the weathering of carbonate minerals, principally calcium carbonate ($CaCO_3$), also dolomite ($MgCO_3$) (Batjes, 1996). When this weathered material is transported to water bodies, it is measured as dissolved inorganic carbon (DIC) comprising bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions, and dissolved CO_2 (Vogel *et al*. 2000), whereas particulate inorganic C (PIC) is mainly derived also from weathering and dissolution of carbonate containing minerals (Stumm and Morgan, 1981, Meybeck, 1982). The relative proportions of these three inorganic forms of C are defendant on pH and a lesser extent temperature, in low pH streams the concentration of CO_3^{2-} is negligible (Stumm and Morgan, 1981). 0.4 $PgCyr^{-1}$ of DIC is exported from the soil to rivers, and then the oceans. Its half of which is returned to the atmosphere during $CaCO_3$ production by marine organisms. The remaining half is buried in deep sea sediments (IPCC, 2001). Methane concentrations, which are controlled by flow rate and degree of anoxia within the catchment, are usually very low in steep, fast flowing sections of streams (De Angelis and Scranton, 1993, Jones and Mulholand, 1998).

2.3 Total organic carbon (TOC)

Organic C consists of DOC and POC. Total amount of DOC and POC was defined as total organic C (TOC). DOC is defined as the carbon that passed through 0.45 μm filter, whereas POC is defined as the carbon that was retained by the filter of this pore size (Thurman, 1985). In flowing stream, especially in TPSF within forest canopy, DOC concentration is higher than that of POC (Yoshioka *et al*. 2002, Alkhatib *et al*. 2007, Miyamoto *et al*. 2009). POC can either be expressed in content of suspended matter (TSS) (Meybeck, 1993).

The load of DOC that was transported from the soil and plants to the rivers and oceans are said to be rather small (0.4 $PgCyr^{-1}$) (IPCC, 2001), but the roles of DOC performed within each of these components is essential. Within the soil, load of DOC are a relatively large source of carbon for microbial activity (Neff and Asner, 2001). The soil also supplies a large proportion of DOC to water bodies where DOC is critical in the provision of energy for heterotrophs (Hader *et al*. 1998, Drakare *et al*. 2002) and pH buffering (Hruska *et al*. 1999). The concentration of DOC within the water body can also alter its colour (Watts *et al*. 2001) and the depth that ultraviolet (UV) radiation penetrates within the water body (Hader *et al*. 1998).

Water from peat swamps containing large amount of organic deposits are usually brown to black stained and very clear (Andriesse, 1988). The dark orange-brown color of water in tropical peatswamps forest indicates a high content of humic acids and clear water also indicates that particulate content in the water is very low.

2.3.1 Sources of TOC

The main sources of organic C in the stream and river are from external sources originated from vegetation (leaching, rhizodeposition, fragmented plant material and directly from litterfall) and soil (leaching, organic matter decomposition and erosion) (Thurman, 1985, Hope *et al*. 1994, Meyer *et al*. 1998) within peatland.

Peatland provide the largest source of DOC and POC to aquatic systems (Hope *et al*. 1997), thus in peatland drainage waters are also associated with high concentrations of DOC and POC (Aitkenhead *et al*. 1999, Billet *et al*. 2004). DOC as well as POC is allochthonous origin i.e. derived externally from terrestrial organic matter (Vannote *et al*. 1980, Fiebig *et al*. 1990, Brooks *et al*. 1999). Only a small fraction of DOC is produced within the water body: sources include DOC leached from leaves, larger particulate organic matter (POM) that is broken down and extracellular releases from plants (Allan, 2001), whereas POC is not formed within the aquatic environment. Concentration and load of DOC and POC are also influenced by other variables such as discharge, rainfall, seasonality, slope and catchment size (Eckhardt and Moore, 1990, Grieve, 1994, Dawson *et al*. 2002) and vary within different streams (Dawson *et al*. 2002, 2004). However, the soil is a large store of organic matter which includes the living biomass (micro-organisms and intact plant and animal tissues), the residues of plants that are beginning to be decomposed by microbes (detritus), and after further microbial decomposition, organic substances which can no longer be recognized as tissues (soil humus) (Brady and Weil, 1999). This large store of carbon ensures high concentrations of DOC are available to move from the soil to the water bodies via a range of hydrological pathways including surface flow and sub-surface flow.

2.3.2 Composition of TOC

DOC is the large part of TOC in tropical peatlands. Compositionally, DOC can be defined as having two components, the humic and the non-humic fraction.

The non-humic fraction (10–25% of DOC) consists of molecules that have an identifiable structure including carbohydrates and fatty, amino and hydroxyl acids (Allan, 2001). The humic substances can be further fractionated according to their hydrophobic and hydrophilic properties, into hydrophobic and hydrophilic acids, base and neutral fractions which are shown in Figure 2.11. The humic fraction has been estimated to contribute between 50 and 75% (up to 90% in strongly colored waters), of the total DOC concentration (Allan, 2001) and has been described as being amorphous, brown or black in color and polydisperse (Janos, 2003). The abundance of each fractions within streamwater varies depend on the source of the DOC. DOC can also be fractionated into compounds, e.g. tannins and sugar (Figure 2.11). The fractions of DOC by Leenheer (2004) were used to gain and determine the source of DOC. Also the fractions of DOC may explain the chemistry of the stream under changing hydrological conditions.

Whereas POC in tropical peatlands is only small part of TOC, the material of POC is making up from coarse and fine materials that were made of various debris, i.e. leaves, grasses and wood (Hedges *et al*. 1986, Ertel *et al*. 1986). In streams water the direct fallout of leaves and wood debris from the canopy is major POC source and also can derives from soil erosion (water and wind erosion).

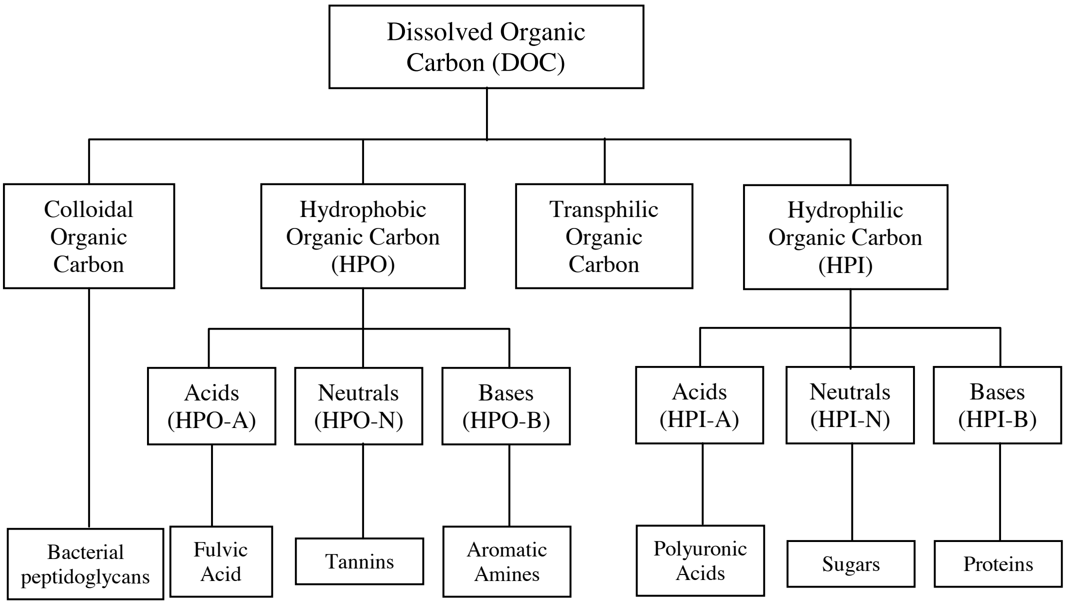


Figure 2.11. DOC fractionation diagram (after Leenheer, 2004)

2.3.3 Function of DOC as part of TOC within water bodies

Dissolved organic C (DOC) is a main part of TOC. In TPSF, DOC concentration is normally higher than POC, so that DOC can reflect the value of TOC. DOC has been identified as an integral component of the global carbon cycle; its functions within the cycle and specifically in water bodies are wide ranging. DOC in water bodies has function as an essential in the provision of energy for heterotrophs (Hader *et al*. 1998, Drakare *et al*. 2002). DOC also protects water organisms from harmful UV radiation, as the concentration of DOC determines how much light penetrates through the water. DOC is also important in pH buffering, by moderating the effects of mineral acid inputs from acid deposition, which increase the acidity of the water (Hruska *et al*. 1999). The concentration of DOC within a water body will also alter its color (Watts *et al*. 2001), and high concentrations of

DOC are responsible for the brown colored water that can be seen in streams draining peaty catchments.

2.3.4 Climate and organic C

Climate conditions at a site are integral to the concentration of organic C that is produced. The production of organic C within the soil, is directly linked with temperature (Andersson *et al*. 2000, Andersson and Nilsson, 2001, Neff and Hooper, 2002), and implications of temperature changes for organic C production under climate change.

Evans *et al*. (2015) collated data from 27 published estimates of DOC flux (include organic C) from near-natural peatland, ranging from a subartic fen to tropical peat swamps. The results indicate that the natural DOC flux from peatlands varies by over an order of magnitude. Fluxes followed a clear latitudinal as well as climatic gradient (temperature and rainfall), from a minimum of 5 g C m^{-2} yr^{-1} in subartic and some boreal peatlands, to a maximum of around 60 C m^{-2} yr^{-1} in tropical peatlands. This suggests that temperature may be the main fundamental control on natural peatland stream DOC fluxes Evan *et al*. (2015).

2.4 Retention and losses of carbon from peat soils

2.4.1 Retention of carbon in peat soils

The soils type have important role in the retention of organic carbon, due to the ability of each soil types in adsorbtion of carbon are different (Moore and Jackson, 1989). The concentration of organic carbon, i.e. DOC and POC, available from the catchment also varies according to soil type. In catchments containing peat with a high proportion of organic soil represent a large potential source of organic C to water bodies (Dillon and Molot, 1997, Aitkenhead *et al*. 1999).

The type of vegetation within a catchment also plays a major role in controlling the concentrations of organic carbon measured within the catchment (Neff and Hooper, 2002). The type of vegetation will determine the quantity and quality of litter input into the catchment and thus the available substrate for decomposition. Vegetation type also influences the decomposability of litter, due to its biochemical properties and to the types of microbial decomposers associated with the vegetation. Vegetation can also alter peat soil drainage, aspect or microclimate, again influencing carbon storage (retention of carbon) (Neff and Hooper, 2002).

2.4.2 Losses to the atmosphere

The main loss of C from soil is in the form of CO_2 from organic matter decomposition. Fires causing direct C emissions to the atmosphere and changes to vegetation and species composition (Harden *et al*. 2000, Mollicone *et al*. 2002) that affect the dynamics of terrestrial C stores for subsequent decades (Lal, 2004). The gaseous C efflux from soils is initially dependent on the rate of production of CO_2 (or CH_4) within the soil-plant root system, and subsequently on the rate of gaseous diffusion and mass flow from soil waters to the atmosphere: a function of soil moisture and textural properties (Pauss *et al*. 1990, Skiba and Cresser, 1991, Whalen and Reeburgh, 2000). Besides diffusion, CH_4 lost to the atmosphere by ebullition or via vascular plants (Moore *et al*. 1998, Whalen, 2005).

2.4.3 Losses due to soil erosion

There are 2 types of erosion by water; sheet erosion as flow over vegetated surfaces and channel erosion, which is limited to where soils lack vegetative cover. Overland flow occurs, removing topsoil and hence substantial organic matter translocation, when runoff is greater than infiltration capacity of the soil (Evans and Brazier, 2005). C and nutrients from water eroded soil is relocated downslope from one area to another or transported to surfaces water (Stallard, 1998, Smith *et al*. 2001, Liu *et al*. 2003). For soils close to the river network, higher stream discharges from increased stream size and energy enhance erosion processes (Lawler *et al*. 1997). River bank erosion and subsequent suspended sediment production can vary within different sites (Stott and Mount, 2004) and impacting on C cycling processes downstream or in lakes (Walling *et al*. 2002, Stott and Mount, 2004). Wind erosion also can cause a substantial loss of soil C in exposed areas and can be transported thousands of kilometres before redeposition, most of it in land (Smith *et al*. 2001, Yan *et al*. 2005). Factors, such as distribution and speed of wind and soil erodibility parameters including dryness, texture and land use establish surface roughness of non vegetated soils to determine the temporal and spatial differences in wind erosion (Böhner *et al*. 2003, Yan *et al*. 2005).

2.4.4 Losses via hydrological processes

The first stage in the loss of soil C to surface waters is the movement of organic matter from soil to interstitial pore waters. Flow paths are mainly determined by topography and soil type. Soil water, travels preferentially along flow paths and is modified as it moves through organic and mineral soil to the groundwater and the river network. Indeed, the distribution of the soils in relation to the drainage system can be a major influence on C inputs to surface water (Billet and Cresser, 1992). In particular riparian soils in controlling C flow (Fiebig *et al*. 1990, Fiebig and Lock, 1991, Smart *et al*. 2001). However, the linkage of soil with the drainage system is temporally dynamic and liable to disturbance (Fraser *et al*. 2001, Billet *et al*. 2006). The transport and temporal variability of organic C in form of DOC and POC losses from the bulk soil is linked to discharge in response to rainfall events and changing flow paths through different soil types containing contrasting amounts of organic matter (Grieve, 1990, Hinton *et al*. 1998).

2.5 Soil acidity and TOC

The acidity of the soil within a catchment will also play a major role in the concentration of DOC that is move to water bodies, as acidity influences the solubility of DOC (Chapman *et al*. 2005). In tropical peatlands, soil acidity (pH) is normally around 3 to 4.

The acidity of the soil is produced by both natural and anthropogenic processes. Within the soil there are numerous processes that produce H^+ ions, thereby altering the soil pH; these include the formation of carbonic acid, processes involved during the accumulation of organic matter, oxidation of nitrogen and sulphur and the uptake of cations by plants (Brady and Weil, 2002). The organic acids that compose DOC are themselves weakly acidic and they contribute to the buffering capacity of water bodies; (Hruska *et al*. 1999) determined that DOC was important in buffering anthropogenic acidification within a pH range of 4.5–5.2. Another input of acidity to the soil is rainwater which is naturally acidic (pH 5.6) as it reacts with atmospheric carbon dioxide to produce a weak carbonic acid (Botkin and Keller, 1997).

These natural inputs into the soil have also been influenced by anthropogenic activity since the mid 19th century, sulphur dioxide and nitrogen oxide species produced through the burning of fossil fuels, hydrochloric acid emitted from coal burning power plants and ammonia from intensive agriculture (Botkin and Keller, 1997) all contribute to observed increases in soil acidity. These pollutants are either deposited directly via dry deposition, or in rainfall in the form of sulphate, nitrate or ammonium (Monteith *et al.* 2001).

Indeed it has been identified that when the pH increases, TOC becomes more soluble as the pH dependent negative charge on the humus colloids increases (Andersson *et al.* 2000). An increase in pH also has a positive effect on the amount of biological activity in the soil (Andersson *et al.* 2000). Another indicator of increased soil acidity is increases in concentrations of the cations, i.e. Na^+, Mg^{2+} and Ca^{2+} which have been observed to correspond with increases in SO_4^{2-} and H^+ ions (Adamson *et al.* 2001). Increasing acidity of soil can lead acid soil leaching to the stream then acidifying water bodies (Harriman and Morrison, 1982).

2.6 Influences of changes in TOC

Increasing TOC concentrations in water bodies would have several implications, including a reduction in the global carbon store, increase in metal content and the color of water bodies so can give impact toward the aquatic ecosystem. For instance, the possibility of reduce the oxygen (O_2) production on aquatic ecosystem.

2.6.1 Reduction in the global carbon store

The peatland carbon store is at particular risk from the effects of climate change. Peatlands hold an estimated one third (455Gt) of the world's total soil carbon stores (Fraser *et al*. 2001) and increasing fluxes of TOC from peat catchments, signals increased loss of carbon from these stores. Global carbon stores is essential for predicting the future changes in their storage capacity, as under changing climates storage of carbon within soils will alter (Post *et al*. 1982).

2.6.2 Water bodies and TOC

Increases in concentrations of TOC as main form of DOC would detrimentally affect receiving water bodies, changing both their colour and potentially metal concentrations. The movement of metals (Grieve, 1984, Lawlor and Tipping, 2003, Martinez *et al*. 2003), and particularly Fe, which also contributes to the colour of the stream (Fenner *et al*. 2001), have found to be highly correlated with DOC, therefore if DOC concentrations increase, corresponding increases of metal concentrations may be measured. Any increase in concentration of metals within streamwater will increase the threat of toxicity to the organisms that live within this ecosystem (Lawlor and Tipping, 2003) and if the water was to be consumed by humans, it would require further water treatment.

Chapter 3

MATERIALS AND METHODS

3.1 Study area

The study area is located on peatland in the south-west portion of Kampar Peninsular, in Pelelawan District of Riau Province, Sumatra, Indonesia. It is approximately 20 km across (Figure 3.1) and lies approximately 130 km east-south-east of Pekanbaru, the capital city of Riau Province.

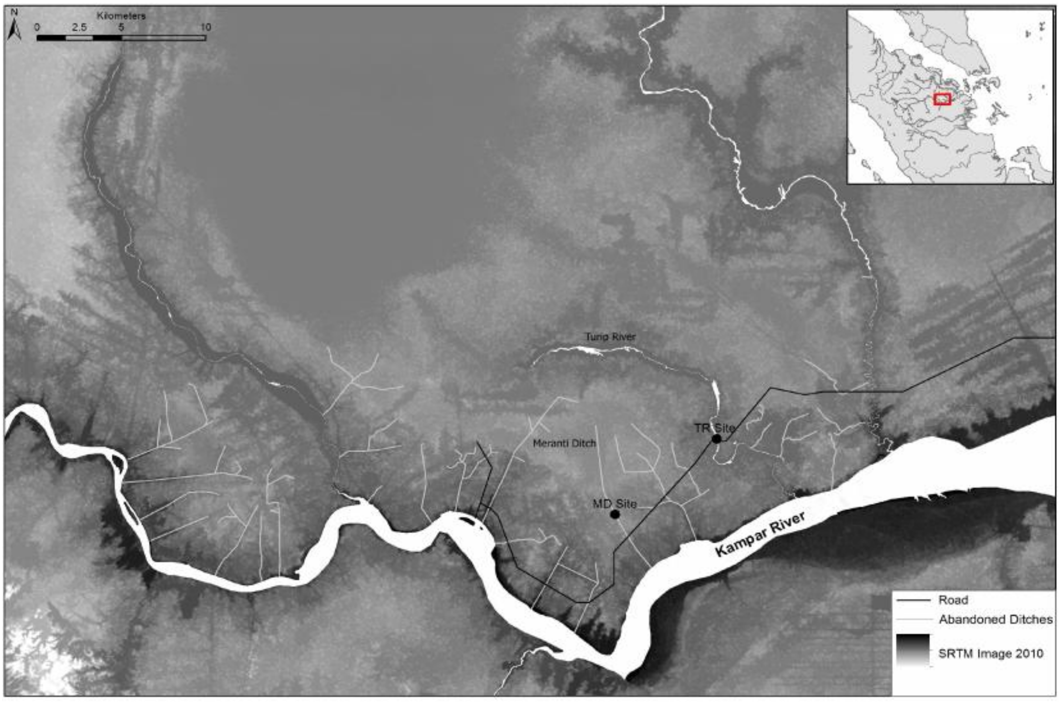


Figure 3.1 Study sites of Meranti Ditch (MD) and Turip River (TR) in the Kampar River system of Riau Province, Sumatra, Indonesia.

Altitudes were derived from the Shuttle Radar Topographic Mission-Digital Surface Model (SRTM-DSM), and by leveling survey on the ground. The landscape within the study area slopes upwards from the tidal Kampar River to a raised peat plain approximately 9 m above sea level.

The underlying geology is dominated by unripened marine clays and alluvium. Mean annual rainfall is 3,300 mm with a brief dry spell in February and a distinct dry in June-August, with mean daily temperature is 27.2 ^{0}C and daily evapotranspiration 3.9 mm (20-year records from Pekanbaru Airport).

The vegetation of the study area consists of tropical peat swamp forest (TPSF) whose structure and composition varies with altitude, the tall diverse mixed forest at sea level beside the Kampar River grading into short pole forest with few tree species at 6 m altitude, then into stunted dwarf forest on the peat plain at 8–9 m a.s.l. The present day condition of the forest also grades in this direction, from almost absent beside the Kampar River, to degraded, and then to relatively intact above 5– 6 m a.s.l. The common tree species of the original forest include *Palaqium* sp., *Payena* spp., *Euginia* sp., *Antidesma bunius*, *Alseodaphne panduriformis*, *Helicia excelsa, Shorea* sp., *Shorea platycarpa* Heim., *Gonystylus* spp. and *Ilex cymosa*. Other vegetation includes an understory of shrubs and young trees.

The lower half of the study area was selectively logged under license from 1985 to 2005, using a light railway to carry timber to the Kampar River. Selective logging typically left 50% or more of the large trees standing, creating 'semi-intact to intact' forest cover in the terminology of Bathgate and Rachmady (2012). From 2001 to 2010 about a half of the previously logged area was subject to further unregulated ('illegal') logging. Excavators were used to create ditches, spaced a few kilometers apart, in order to float the logs to the nearest point on the Kampar River. Although subsequently disused, these logging ditches continued to drain the peatland (Figure 3.1). In addition, some accessible riparian areas along

Kampar River were cleared for unregulated agriculture burning. The result was a patchwork of intact forest, degraded forest where fewer than 50% of original large trees remained, and scrubland (Bathgate and Rachmady 2012).

In 2010 Riau Andalan Pulp and Paper (RAPP) developed part of the study area as a fibre plantation concession. Land use zones were arranged according to altitude, with a community livelihood plantation beside the Kampar River, *Acacia* plantation at 3–5 m a.s.l., and above that a zone of regenerating natural forest to form a buffer for the conserved zone. Within the conserved zone, the abandoned logging ditches were surveyed for subsidence and the depressions ('sunken valleys') they had created were closed with permanent weirs in order to restrict drainage and rewet the peat. The conserved forest is monitored for ongoing peat subsidence, trends in TPSF biomass recovery, and wildlife (Bathgate and Rachmady 2012).

3.2 The study streams and their catchment

Two watercourses were selected for hydrological measurement. One is a small stream named Meranti Ditch (MD) and the other is a river named Turip River (TR) (Figure 3.1). The catchments of MD and TR are formed entirely of recent peat deposits (Brady, 1997), and high concentrations of humic acids in stream runoff are indicated by the dark orange-black colour of the water. Sampling of peat profiles with a Russian pattern corer (Belokoptyov and Beresnevich 1955, Jowsey 1965) showed that the peat layer at the MD and TR sampling stations was 6 m and 7 m thick, respectively.

MD was excavated in 2001 for logging purposes. It is 2 m wide and 2 m deep, with a mean gradient of 0.0004 (derived from SRTM-DSM data). Topographic leveling in 2010 showed a subsided valley up to 1 m deep centered on the ditch (Bathgate and Rachmady 2012). The small MD catchment lies on a peat dome with semi-intact T PSF and terminates in the buffer zone of regenerating forest between conserved T PSF and *Acacia* plantation. In 2010 a series of six weirs was installed on MD to restrict water discharge, maintain high water table in the ditch and adjacent peat land during dry spells, and thus promote conservation of both the peat soil and the forest. The ditch contains water even during periods of lowest rainfall, and adjacent land is shallowly flooded at times of peak rainfall. Since 2010, peat has continued to subside at mean rates of 1 cm p.a. in the upper MD catchment and 2 cm p.a. in the buffer zone (RAPP, unpublished data).

TR is a natural river (without artificial regulation) with a larger catchment than MD (Figure 3.2), extending from its origin on the peat plain to the TR sampling site just upstream of the road. The flatness of the peat plain means that the catchment boundary cannot be precisely delineated from SRTM-DSM data. The river has a mean gradient of 0.0002. The TR catchment is almost entirely covered by peat swam forest whose condition is estimated from Landsat 8 satellite images and high-resolution aerial photography to be 75% intact and 25% degraded. A small area of plantation located upslope of the road is drained by a managed ditch that discharges into the TR downstream from the study catchment.

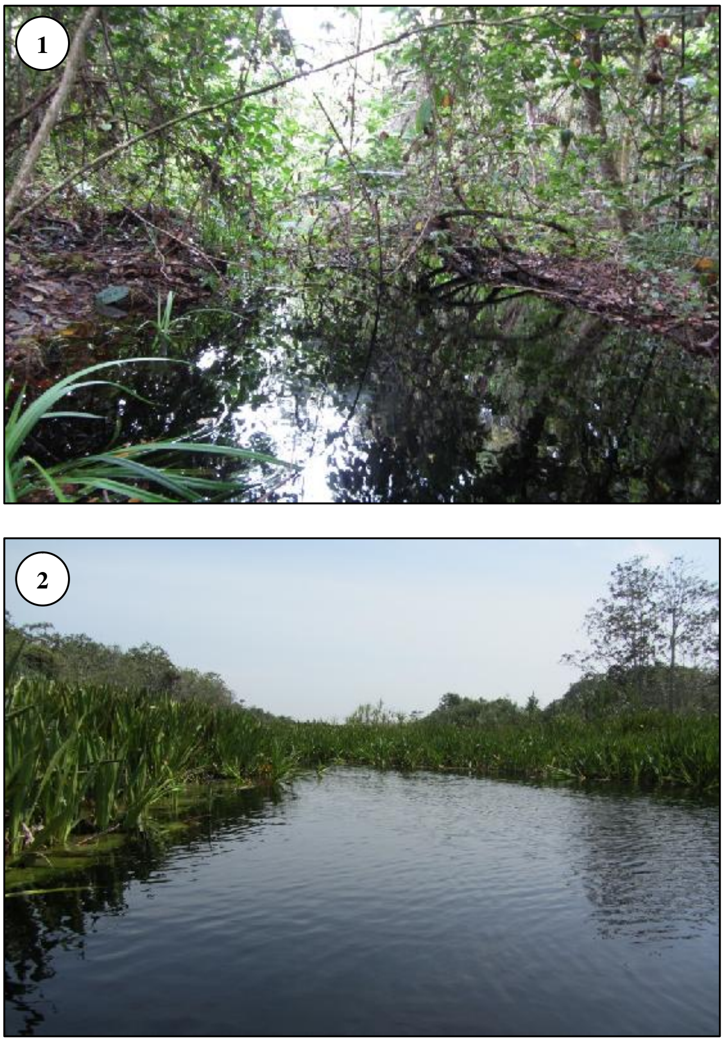


Figure 3.2 Small artificial ditch (MD) picture 1 and Turip River (TR) picture 2.

3.3 Hydrological measurements

3.3.1 Stream water level (*SWL*)

Stream water level (SWL) was measured near the downstream ends of both catchments, at 0° 15' 0.1" N, 102° 34' 29.6" E for MD, and 0° 17' 26.3" N, 102° 37' 50.4" E for TR (Figure 3.3). SWL at each locations was measured 'continuously' (at intervals of 30 minutes) using an absolute pressure type water level data logger (Onset Hobo U20-001), which was installed inside a perforated

PVC pipe set in the stream. Barometric pressure was also measured at both sites to enable conversion of the raw water pressure data into actual water levels. The measurements at MD were conducted from 24 May 2012 to 12 December 2013 for MD and at TR from 25 May 2012 to 08 February 2013 for TR until the logger was stolen (after data download on 08 February 2013). The data indicated that there was no tidal effect on SWL at either of these locations.

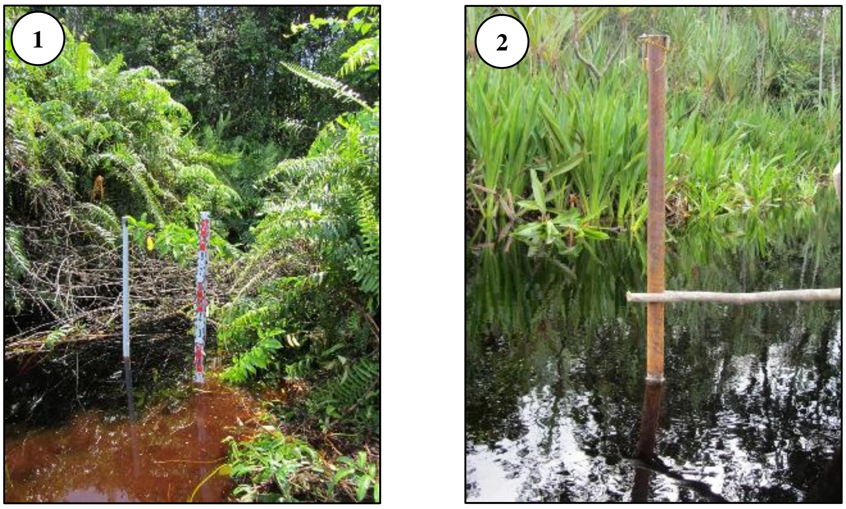


Figure 3.3 Stream water level measurements and water level stage in MD picture 1, stream water level measurement in TR picture 2.

3.3.2 Ground Water depth (*GWD*)

Ground water depth (GWD) was measured in both catchments over the same time periods (Figure 3.4), using water level data loggers of the same type with data logger to measuring water level in streams, installed in dipwells made from 5 cm internal diameter perforated PVC pipe that penetrated 2 m into the mineral substratum (and were thus anchored securely). For accessibility reason, the two GWD measurement sites were located only ~300–400 m from the stream, at 0° 15' 12.5" N, 102° 34' 34.0" E for MD, and 0° 17' 37.8" N, 102° 37' 58.7" E for TR.

Figure 3.4 Groundwater depth measurements in TR picture 1 and in MD picture 2.

3.3.3. Stream discharge (*Q*)

Flow rate was measured at the locations on MD and TR where the SWL data were collected (which had stable stream cross-sections) (Figure 3.5), using an electromagnetic velocity meter (DENTAN TK–105x). Flow data were gathered 12 times at each site between June 2012 and March 2013. Measurements were made at almost weekly intervals during June and July 2012 (7 in MD, 8 in TR), then once a month from November 2012 to March 2013 (5 in MD, 4 in TR). Streamflow was not measured during August, September and October in 2012.

Each measurement was performed by dividing the cross-section of the stream into more than ten subsections, then measuring flow velocity at a single point in each subsection. This point was located at the lateral centre of the subsection, at a height above the stream bed calculated as 40 % of the average of the water depths at the two ends of the subsection. Each flow velocity measurement was repeated more than three times and averaged, then multiplied by the area of the subsection to derive its flow rate (m^3 s^{-1}). Total flow (discharge) rate (*Q*) was calculated by summing the subsection values across the full width of the stream.

Figure 3.5 Flow rate measurements in the downstream end of Turip River (TR).

For each stream, the 12 flow measurements were used to create a discharge rating curve expressing the relationship between *Q* and SWL. The discharge rating curve was then used to convert the continuous SWL data to continuous flow rate data for the whole period of measurement. For the calculation of annual discharge, the missing SWL data for TR (08 February to 12 December 2013) were reconstructed by estimating SWL values from the moving average of the previous three days' GWD data when the water table was below ground level, and taking SWL = GWD when the GWD data indicated that the ground surface was flooded.

3.3.4 Rainfall (*P*)

Rainfall was recorded by a 0.5 mm tipping bucket rain gauge (Ota Keiki Seisakusho Co., Ltd., OW-34-BP) equipped with a data logger (Onset Hobo UA003-64) sited in an open area near the MD stream measurement site (0° 15' 0.2" N, 102° 34' 30.8" E) (Figure 3.6). A similar rain gauge installed near the TR stream gauging site malfunctioned, so the MD rainfall data were used to represent both sites.

Figure 3.6 Rainfall recording near MD stream

3.4 Catchment areas

It is not easy to define catchment areas on the almost flat PSF landscape, and estimates of catchment areas in PSF are scarce. Siderius (2004) and Baum *et al.* (2007) estimated their catchment areas from SRTM DEM (digital elevation model) data by using the Analyst function of ArcGIS.

In this study, the catchment areas of MD and TR stream gauging sites were estimated using two approaches:

The first was a water balance approach, in which runoff depth (*q*) was calculated by subtracting an assumed evapotranspiration (*ET*) value from rainfall (*P*), then the catchment area (*A*) was determined by dividing total discharge by the runoff depth (*q*). *ET* was determined using data from the studies conducted by Kumagai *et al*. (2005) and Hirano *et al*. (2014) in tropical peatland on Borneo, and by Baum *et al*. (2007) on Sumatra. This approach, any contribution of ground water inflow and outflow to catchment water stores over the study period was not estimated, rather it was assumed the groundwater inflow and outflow did not change the stored water volume in each catchment.

The second approach involved spatial analysis of SRTM-DSM data by using the function of ArcGIS Spatial Analyst extension tool. SRTM-DSM data was obtained from USGS Earth Explorer website (http://earthexplorer.usgs.gov/), enhanced with data from the RAPP topographic survey, and identification on high resolution images of ditches and other reference features within the study area. Where the catchment boundaries could not be defined from topographic data they were estimated by assuming that they lay midway between watercourses, including the abandoned logging ditches.

3.5 Water sampling and analytical procedures

Streamwater samples were collected in 250 ml plastic bottles from ~ 30 cm depth below the water surface, without filtering, at the same times and locations as the flow rate measurements were made. Electrical conductivity (EC) (Horiba Twin Cond EC meter) and pH (Horiba Twin pH meter) were measured directly at the sites each time water samples were collected. There was no water sampling between the end of July and early November in 2012. This was a period of low rainfall and low flow rate, which would have only a small effect the on load and yield results.

Rainwater was sampled six times at MD and seven times at TR (from 28 May to 27 July 2012 for both sites). It was collected in 250 ml plastic bottles, each equipped with a funnel and nylon net cover (mesh size 0.1 mm) to exclude insects, whose rim was set 150 cm above ground level. These rainfall collectors were located in open areas well away from any vegetation canopy effect, and the bottles were changed at each site visit.

Streamwater and rainwater samples were stored at low temperature (*ca.* 5^0C) in the dark until analysis. TOC and DOC concentration were measured in the laboratory using a TOC analyzer (Shimadzu TOC-VcpH). TOC concentrations were determined on unfiltered water samples. DOC is defined as C that can pass through a 0.45 μm filter, and POC is the C that is retained by a filter of this pore size (Thurman 1985). Thus, to measure their DOC concentrations, the water samples were passed through 0.45 μm glass fibre filters before analysis. The POC concentration for each sample was determined as the difference between its TOC and DOC concentrations, i.e. POC was not specifically measured.

Due to the remote location of the study area, the water samples were transported over a long distance and stored for some time before analysis in the laboratory. Thus, there was potential for changes in their chemistry, including organic C content, during transportation and storage. To assess any POC decomposition during storage, on one occasion at four sites we collected duplicate water samples from which we removed particulate organic C (POC) at the sampling site, immediately after collection, using a syringe with a glass fibre filter (0.45 μm pore size). These water samples were transported to the laboratory in 20 ml vials, which were stored with the corresponding 250 ml samples for 35–38 days before analysis and comparison of DOC concentrations. This comparison was performed on streamwater and groundwater samples from MD, TR, an *Acacia* plantation area approximately 6 km from TR at Meranti (Riau Province, Sumatra) and Taruna Canal, 20 km from Palangka Raya in Central Kalimantan (Borneo). We found that both unfiltered and filtered samples of the same water returned the same C concentrations (linear regression $R^2 = 0.99$), i.e. that POC had not been transformed into DOC during storage of any of these samples. In Figure 3.7 the difference DOC concentration among water sampling methods are shown.

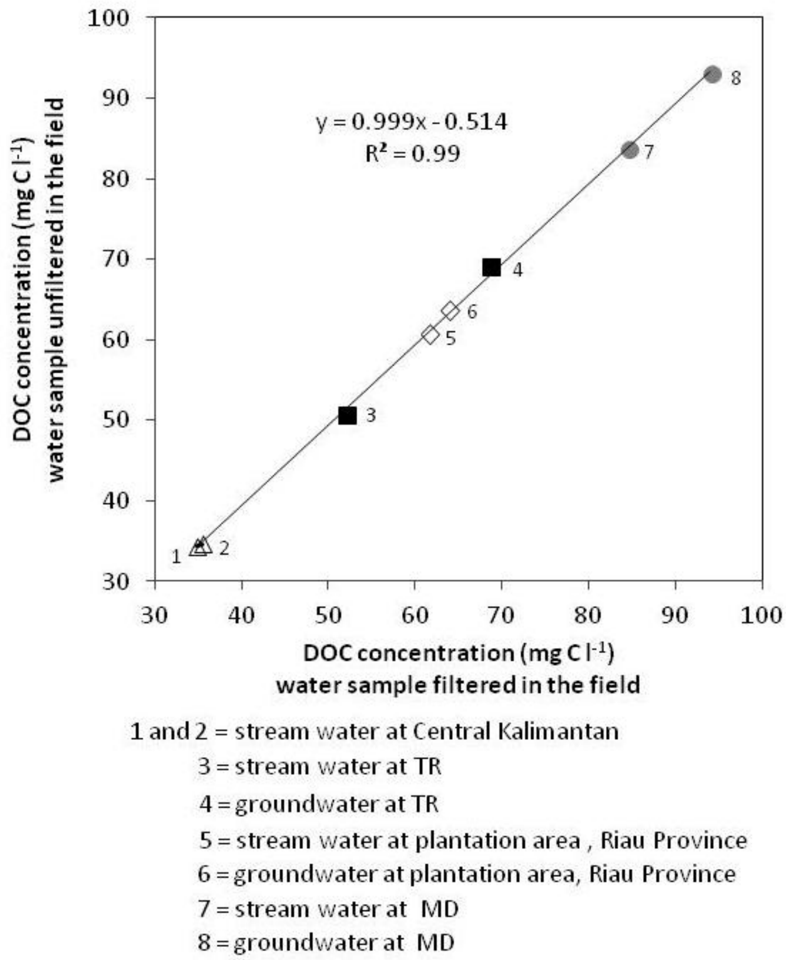


Figure 3.7 Comparison of dissolved organic carbon (DOC) for defining the effect of storage of 35 to 38 days by two methods of water sampling in the field.

3.6 Calculation of carbon loads and yields

The carbon data were adjusted for the organic C concentration reduction effect that occurs during storage by applying a DOC loss rate factor of 0.039 % day^{-1} (Peacock *et al*.2015). The maximum storage time for our water samples was 138 days.

TOC or DOC loads were derived by multiplying the values of instantaneous concentration of TOC or DOC by the flow rate at the time of sampling.

Then, for both MD and TR, the relationship between organic C load ($L_{(TOC)}$ or $L_{(DOC)}$ and flow rate (Q) (the L-Q formula) as follow:

In Md $\quad L_{(TOC)} = 92.22\,Q - 0.29 \quad (1)$

$\quad L_{(DOC)} = 89.83\,Q - 0.26 \quad (2)$

In TR $\quad L_{(TOC)} = 53.71\,Q - 7.38 \quad (3)$

$\quad L_{(DOC)} = 52.91\,Q - 4.51 \quad (4)$

The R^2 values for all of these equations exceeded 0.99 for each equation as shown on Figure 3.8. To determine 'continuous' organic C load throughout the observation period, the L-Q formula was applied to the flow rate data (Q). Total quantities of TOC and DOC ($\sum L_{(TOC)}$, $\sum L_{(DOC)}$) discharged during a period of 365 days of continuous hydrological observations (01 June 2012 to 31 May 2013) at MD and at TR were then derived by summing the 30-minute values of $L_{(DOC)}$ and $L_{(TOC)}$) over this period.

The total quantity of POC discharged over the same period $\sum L_{(POC)}$, was obtained by subtracting $\sum L_{(DOC)}$ load from $\sum L_{(TOC)}$.

$$\sum L_{(POC)} = \sum L_{(TOC)} - \sum L_{(DOC)} \quad (5)$$

The organic C yields were obtained by dividing organic C discharge totals by the appropriate catchment area (A).

For comparative purposes, we also calculated long-term loads (DOC and TOC) using periodic data. In this case, the trapezoidal method (Atkinson 1989) was used to estimate annual load from the instantaneous DOC and TOC loads calculated above.

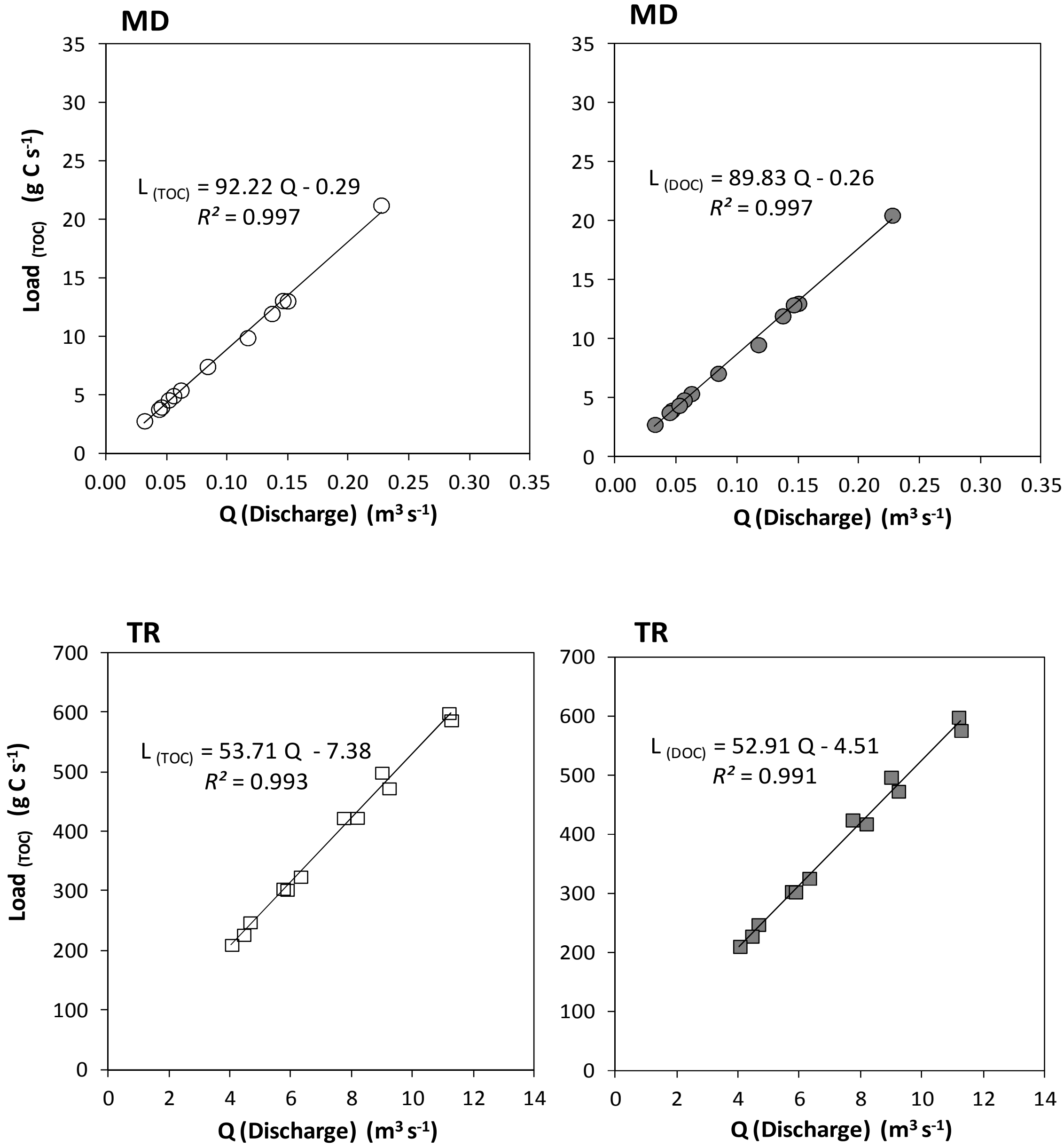


Figure 3.8 Relationship between Load $_{(TOC)}$ as well as Load $_{(DOC)}$ and discharge both in MD and TR.

3.7 Long-term apparent rates of carbon (C) accumulation (LARCA)

Long-term apparent rates of C accumulation (LARCA) were calculated using peat basal ages (peat ages date of initiation). According Tolonen and Turunen 1996, Clymo and Turunen 1998, LARCA was calculated as total peat C divided by peat basal age, whereas total peat C was obtained by multiplying amount of percentage C content in peat with peat bulk density and the thickness of peat. Brady (1997) was reported the peat ages in Sumatra TPSF 4000–4500 years BP including our study site Meranti ditch (MD) and Turip River (TR). The average percentage C content values of TPSF in Indonesia i.e., 49.5% and bulk densities was 0.13 g cm^{-3} (Warren *et al*. 2012), it's applied for MD and TR site. The thicknesses of peat were 6 m and 7 m for MD and TR respectively.

Chapter 4

RESULT

4.1 Rainfall, stream water level, and groundwater depth

Monthly rainfall at the study site and the airport of Pekanbaru (127 km west-north-west from MD) during the study period is shown in Figure 4.1.

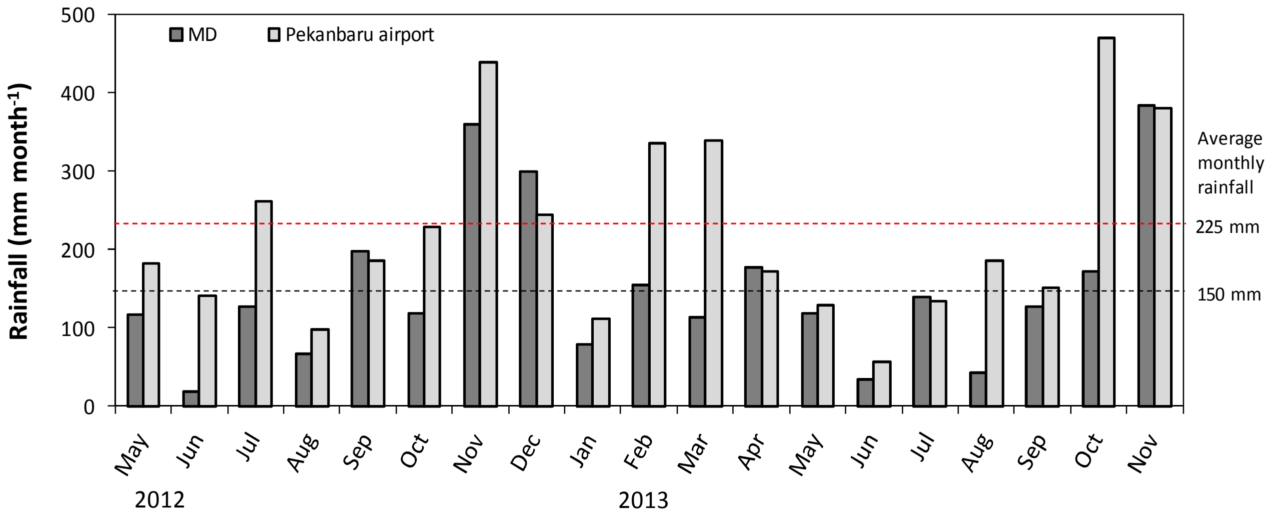


Figure 4.1 Monthly rainfall at the Meranti Ditch (MD) study site and Pekanbaru Airport, May 2012 to November 2013.

The difference in rainfall between rainy and dry seasons was clear. There was also a significant differences in total annual rainfall between this two locations for the year June September 2012 to May 2013), when 1,831 mm was recorded at MD and 2,685 mm at Pekanbaru airport.

Figure 4.2 shows the progress of Stream water level (SWL) and groundwater depth (GWD) at both sites. The water level in stream and peat rose rapidly after each rainfall events then gradually receded due to drainage and evapotranspiration. At MD, stream water level (SWL) rose immediately in response to rainfall, whereas the response at TR site was delayed. This is attributed to the differences in characteristic of the two catchments (MD and TR). Stream and peat water levels were high during the rainy season (September to December) and low throughout the (longer) dry season (January to August).

SWL and GWD data for both sites are shown in Figure 4.2. The patterns of SWL and GWD fluctuation were closely similar in the two catchments, suggesting that there was no significant deep groundwater contribution to stream flow. During the monitoring period, the water table at MD was always below the ground surface, even in the rainy season. Thus, the highest position of the water table relative to the ground surface (which displayed a type of hummock-hollow microtopography) was consistent with water discharge occurring by shallow subsurface flow. In contrast, the groundwater level at TR became much higher than the ground surface at certain times of year (from the start of the record until June 2012, November 2012 to January 2013, and after November 2013). During these periods of high water table, the ranges and patterns of fluctuations in SWL and GWD were very similar and responses to rainfall events were not apparent (Figure 4.2). This indicates that the stream flooded during the rainy season, inundating the adjacent peatland. The fluctuations of stream and groundwater levels during the dry season had a different character. Then, although the general trends in GWD and SWL fluctuations were quite similar, the response of GWD to each rainfall event was much sharper and more immediate than the response in SWL, which was slight at most. It appeared that GWD in the peatland responded directly to rainfall, discharge and evapotranspiration but the maximum drawdown of the water table was controlled by the water level in the stream.

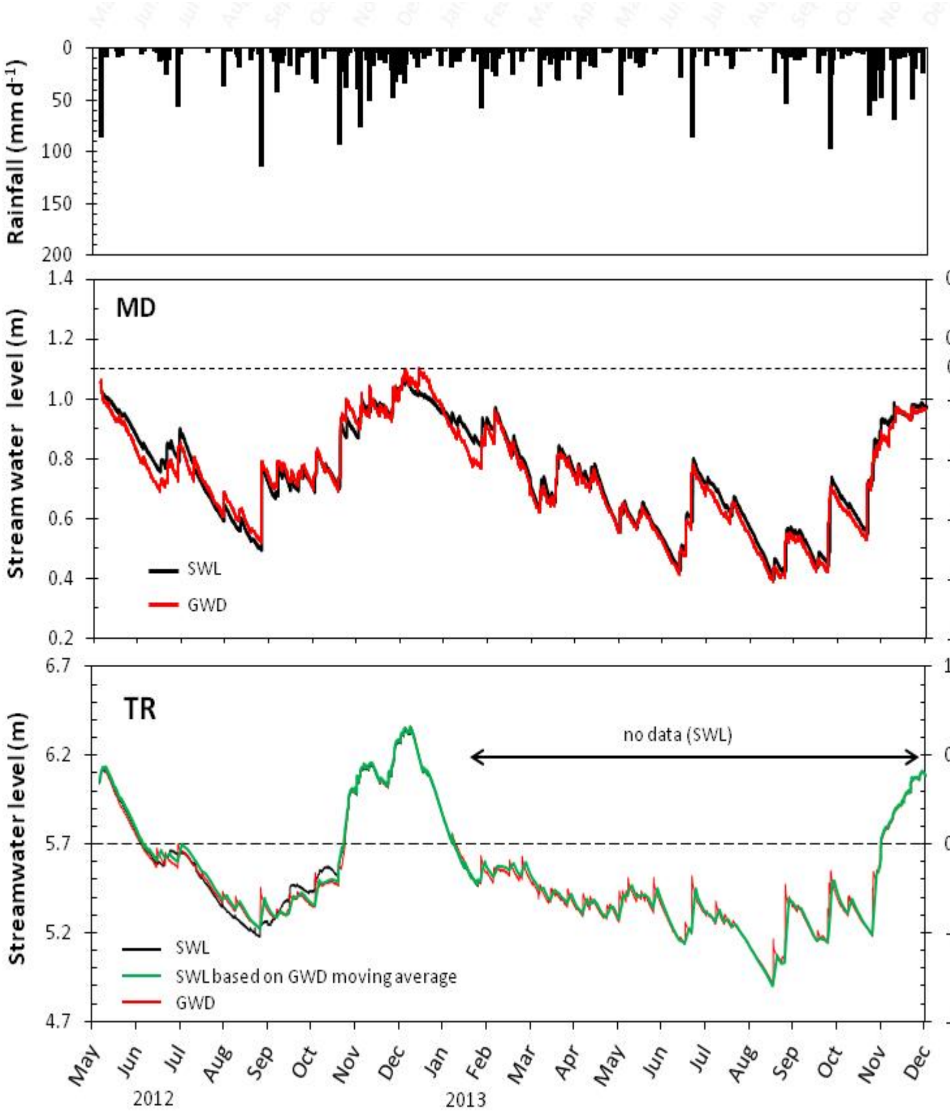


Figure 4.2 Rainfall (top pane), stream water level (SWL) and groundwater depth (GWD) (middle pane) measured at Meranti Ditch (MD); and SWL and GWD measured at Turip River (TR) together with SWL estimated from moving averages of GWD for that location (bottom pane)

4.2 Stream discharge

From the relationships between Q (stream discharge, $m^3 s^{-1}$) and h (SWL, m) for MD and TR, the following discharge rating equations were obtained:

In MD $Q = 0.21 h^{6.09}$ $0.72 < h (m) < 0.96$ $(R^2 = 0.86)$ *(6)*

In TR $Q = 13.9 h – 69.8$ $5.3 < h (m) < 5.9$ $(R^2 = 0.63)$ *(7)*

And the discharge rating curves for MD and TR are shown in Figure 4.3

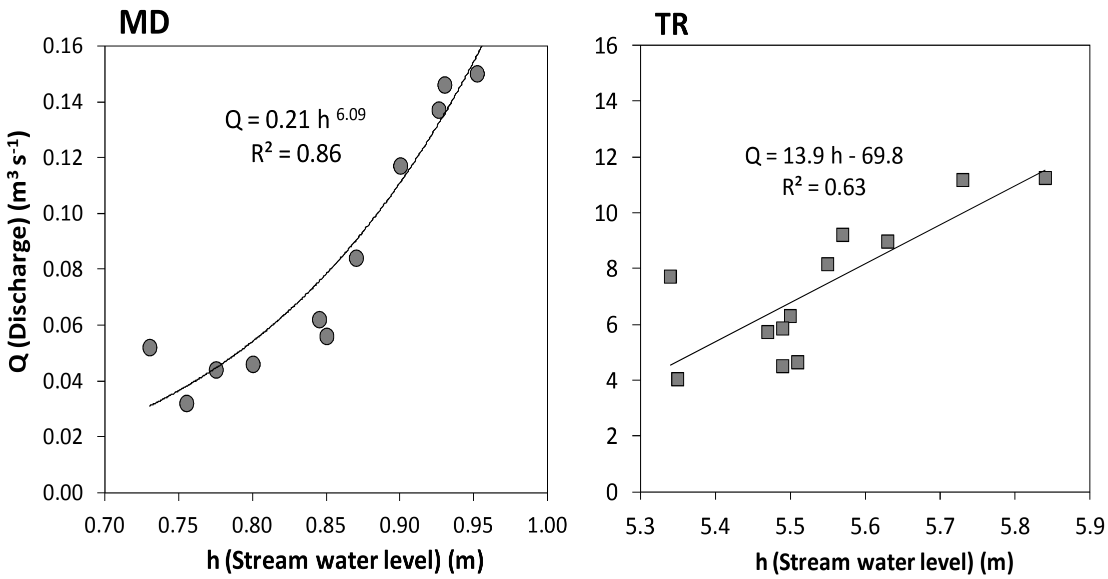


Figure 4.3. Discharge rating curves for Meranti Ditch (MD) and Turip River (TR).

The continuous discharge records generated by applying these rating equations to continuously recorded stream water level (SWL) are shown in Figure 4.4 and Figure 4.5. The continuous discharge data for TR was shorter than the period of measurement for MD, due to the loss of the logger. Based on SWL that were obtained from GWD moving average we could get the continuous discharge during period monitoring.

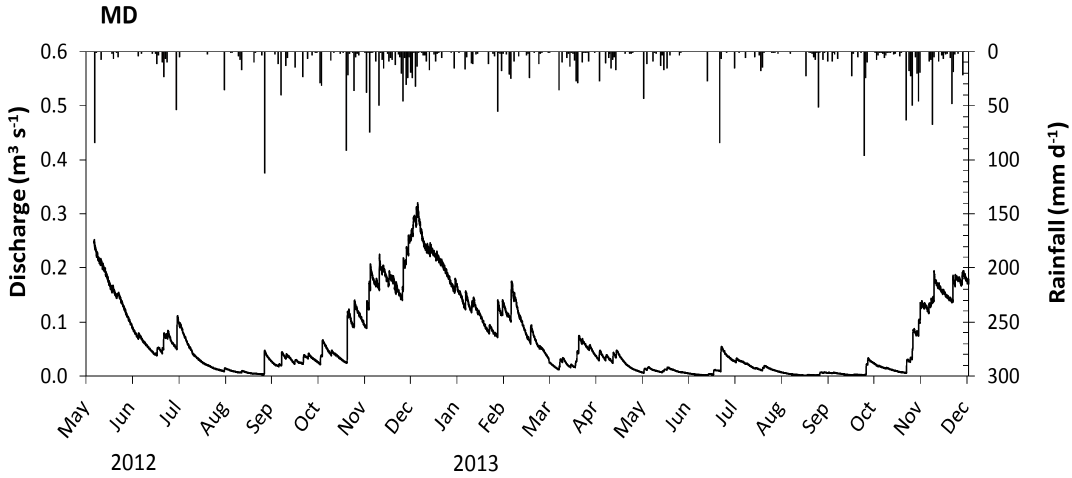


Figure 4.4 Discharge from Meranti Ditch (MD).

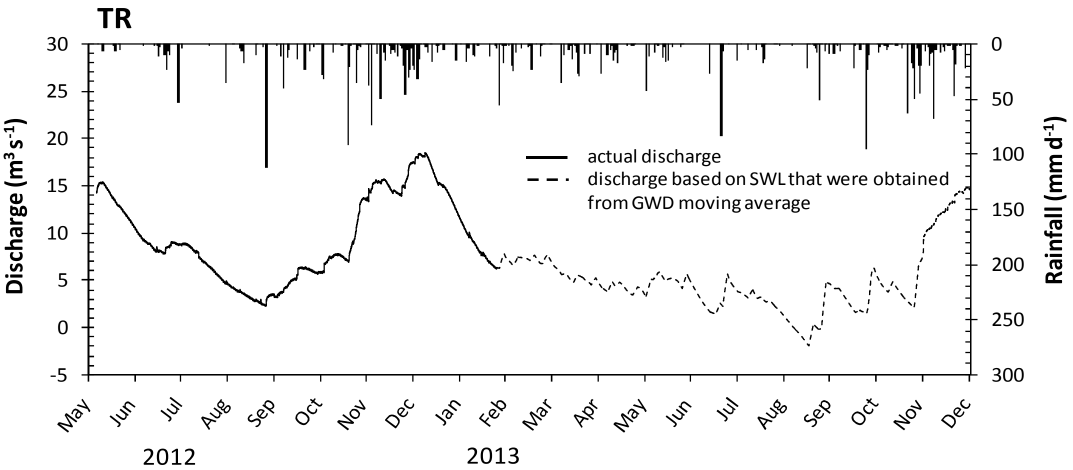


Figure 4.5. Discharge from Turip River (TR).

Table 4.1 shows the discharge characteristics for both sites. In MD, the average discharge was 0.10 $m^3 s^{-1}$ while in TR it was 9.27 $m^3 s^{-1}$. The coefficient of stream flow regime (maximum discharge / minimum discharge) for the 259- days period considered was 107 in MD and 8 in TR, indicating that the difference in discharge between dry season and rainy season is not high in TR. The larger discharge and more stable flow regime of TR is presumably consequence of its larger catchment.

Table 4.1 Discharge characteristics of Meranti Ditch (MD) and Turip River (TR), calculated for the period 25 May 2012 to 08 February 2013 (259 days). (Q_{max} / Q_{min}) is the coefficient of streamflow regime.

Site	Q_{max} (m^3s^{-1})	Q_{ave} (m^3s^{-1})	Q_{min} (m^3s^{-1})	Q_{max} / Q_{min}
MD	0.32	0.10	0.003	107
TR	18.55	9.27	2.20	8

4.3 Catchment areas

For estimation of catchment area using the water balance approach, water loss by evapotranspiration was assumed to be 60%, 65%, and 70% of the total rainfall recorded at MD. The resulting catchment area estimates of MD ranged from 4.2 to 5.6 km^2, while that of TR ranged from 401 to 535 km^2 (Table 4.2). Using the spatial analyst of SRTM-DSM, the catchment area was 3.6 km^2 for MD and 420 km^2 for TR (Table 4.2). To test the accuracy of SRTM-DSM result, water balance was back-calculated. This calculation indicated that the fraction of total rainfall lost through ET was 53 % in MD and 62 % in TR. Essentially, both methods are approximate, and there was no significant difference between the estimates obtained using the two approaches. For the calculations of carbon yields and loads presented here we adopted catchment area values generated using the water balance approach.

Table 4.2 Derivation of catchment area estimates, from the water balance for the period 25 May 2012 to 08 February 2013 (259 days). P = total observed rainfall at MD, ET = evapotranspiration, q = runoff depth, discharge = total observed stream discharge. Catchment area estimates derived by spatial analysis of SRTM-DSAM data are shown for comparison.

Site	P (mm)	ET (estimated)		q (mm)	discharge (m^3)	catchment area (km^2)	
		(%)	(mm)			from water balance	using SRTM-DSM
	i	ii	iii =(i*ii)/100	iv = i – iii	v	vi = $(v/iv*10^3)/10^6$	
MD	1,291	60	775	516	2.17E+06	4.2	3.6
		65	839	452		4.8	
		70	904	387		5.6	
TR	1,291	60	775	516	2.07E+08	401	420.0
		65	839	452		458	
		70	904	387		535	

4.4 TOC, DOC, and POC concentrations in rainwater, streamwater and its relationship with some parameters.

The concentrations of DOC in rainwater and TOC, DOC, POC in stream water are shown in Figure 4.6. TOC concentrations ranged from 85 to 94 mg C l^{-1} at MD and from 50 to 58 mg C l^{-1} at TR. For both streams, most of the TOC was in the form of DOC with a range of 82 to 90 mg C l^{-1} for MD and of 49 to 57 mg C l^{-1} for the TR. Only a small portion of TOC was in the form of POC (0.2% to 5%, or around 0.2 mg C l^{-1} to 4.5 mg C l^{-1}). It was clear that almost all of the TOC contained in T PSF streamwater was in the form of DOC. The TOC concentration was higher at MD than TR.

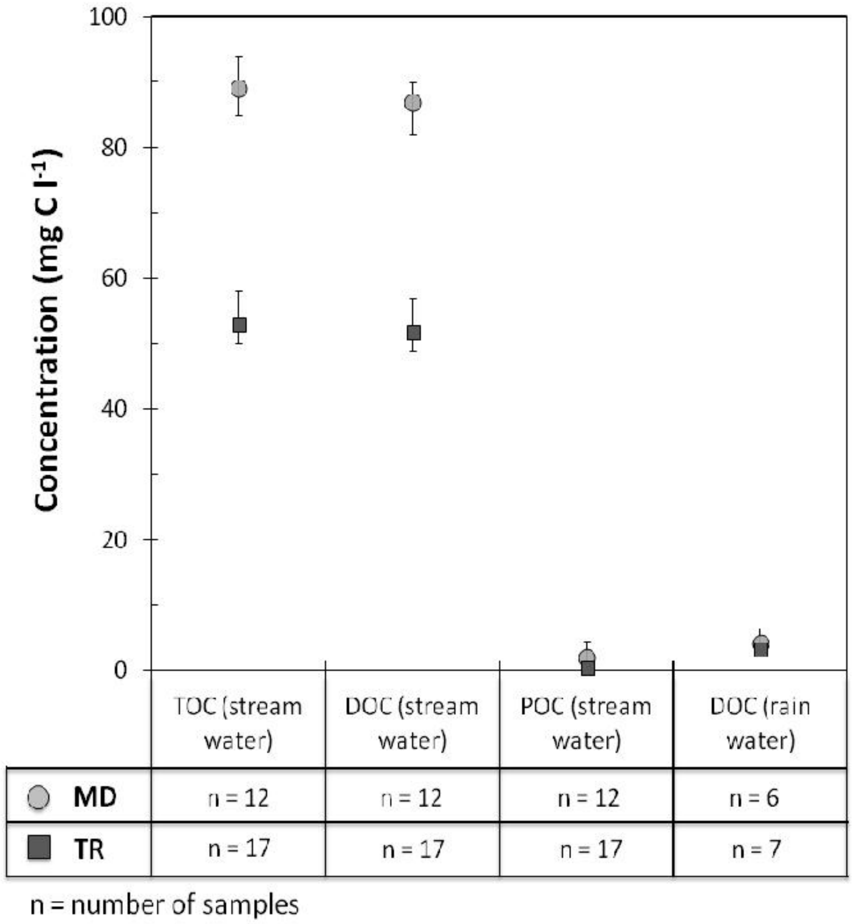


Figure 4.6 Organic carbon concentrations in Meranti Ditch (MD), Turip River (TR) and rain water. Error bars indicate the maximum and minimum values observed.

As shown in Figure 4.7, the TOC and DOC concentrations in the streamwater at MD and TR were fairly stable (*SD* = 2.07 mg C l^{-1} for MD and 2.05 mg C l^{-1}, for TR) and were not affected by the discharge (R^2 between 0.05–0.20, and ϱ = 0.15–0.51).

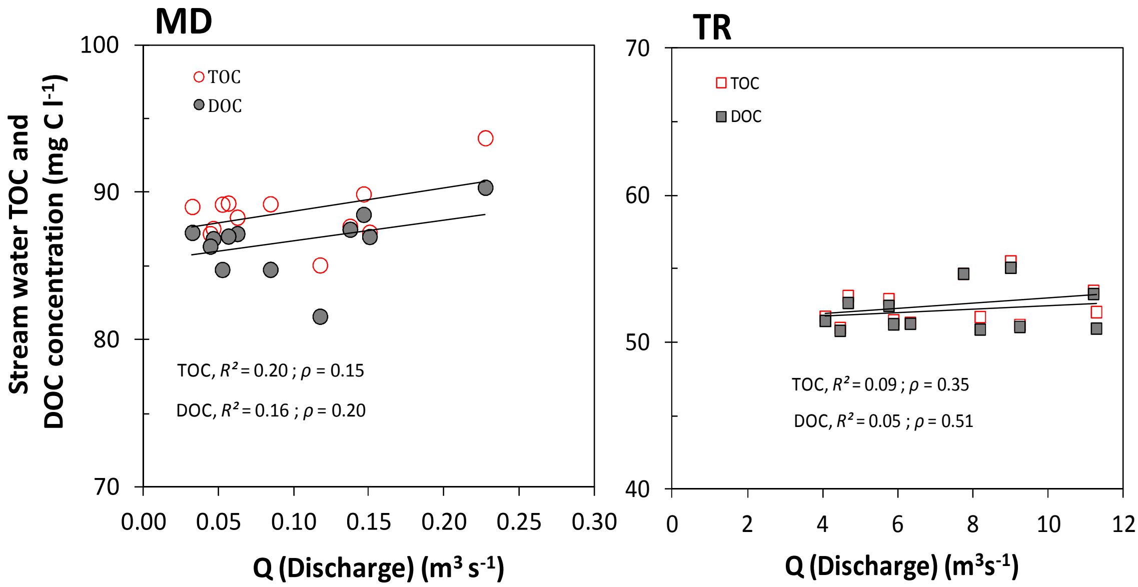


Figure 4.7 Relationship between streamwater discharge with total organic carbon (TOC) and dissolved organic carbon (DOC) concentrations in Meranti Ditch (MD) and Turip River (TR).

Linier regression calculations in Microsoft Excel indicate the TOC and DOC concentrations not affected by discharge rate (R^2 = 0.05–0.20, ϱ = 0.15–0.51) shown in Figure 4.7, and were not related to groundwater depth despite some groundwater depth fluctuations (R^2 = 0.003–0.05, ϱ = 0.42–0.86) it's shown in Figure 4.8. Streamwater pH ranged from 3.4 to 4.1 at both sites (*SD* = 0.2 and 0.1) and did not affect the TOC and DOC concentrations it's shown in Figure 4.9 (R^2 = 0.007–0.08, ϱ= 0.44– 1.81). Figure 4.10 shown the relationship between TOC and DOC concentrations and streamwater EC was not significant for either site (R^2 = 0.003–0.10, ϱ = 0.38–0.89).

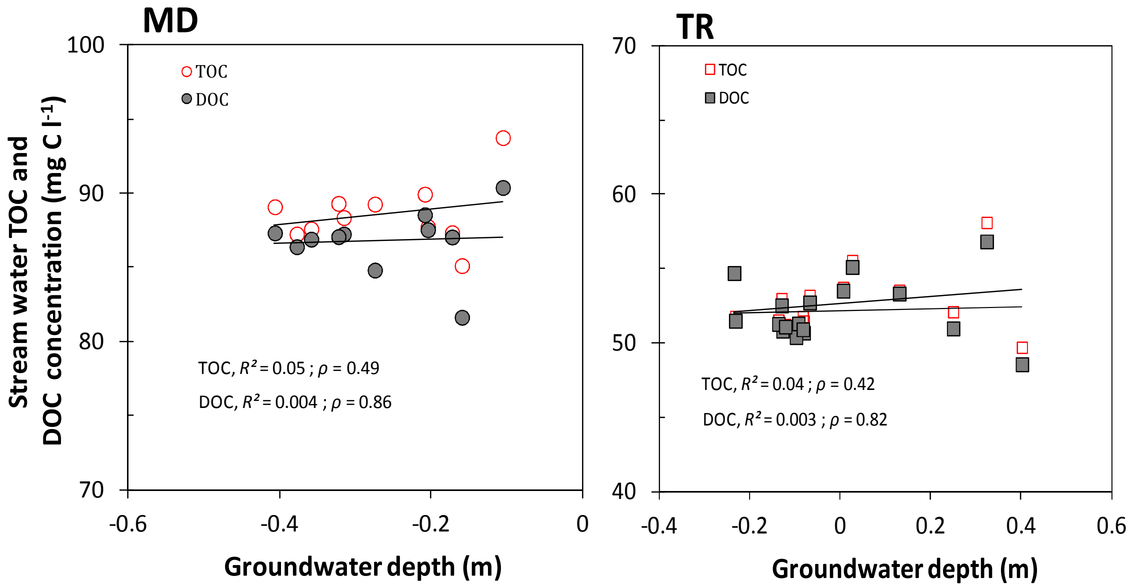


Figure 4.8 Relationship between groundwater depth and streamwater total organic carbon (TOC), dissolved organic carbon (DOC) concentrations in Meranti Ditch (MD) and Turip River (TR).

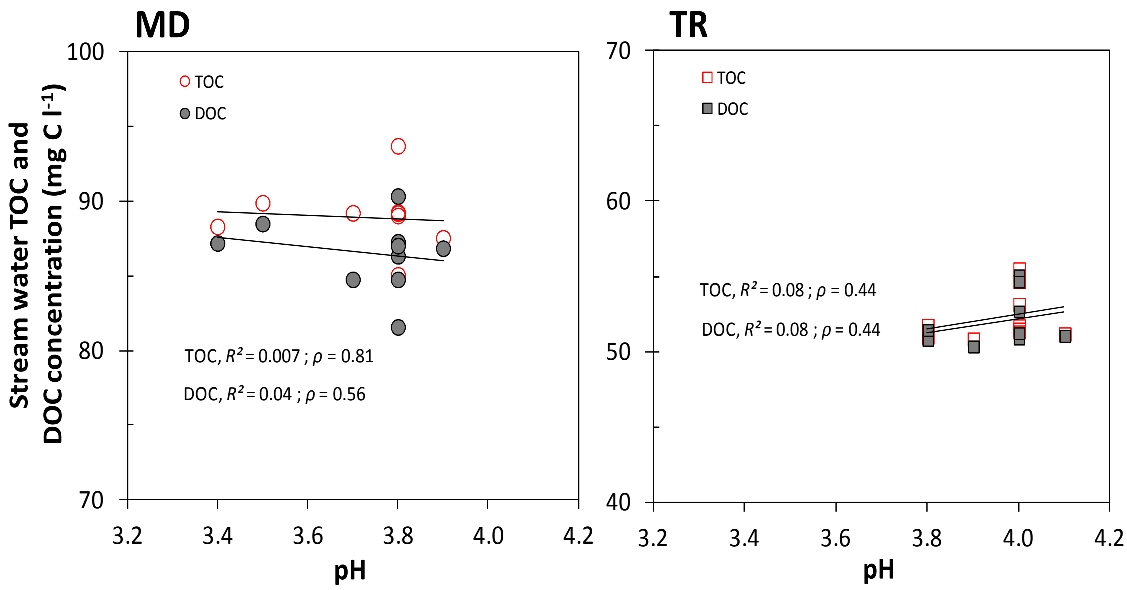


Figure 4.9 Relationship between pH and streamwater total organic carbon (TOC), dissolved organic carbon (DOC) concentrations in Meranti Ditch (MD) and Turip River (TR).

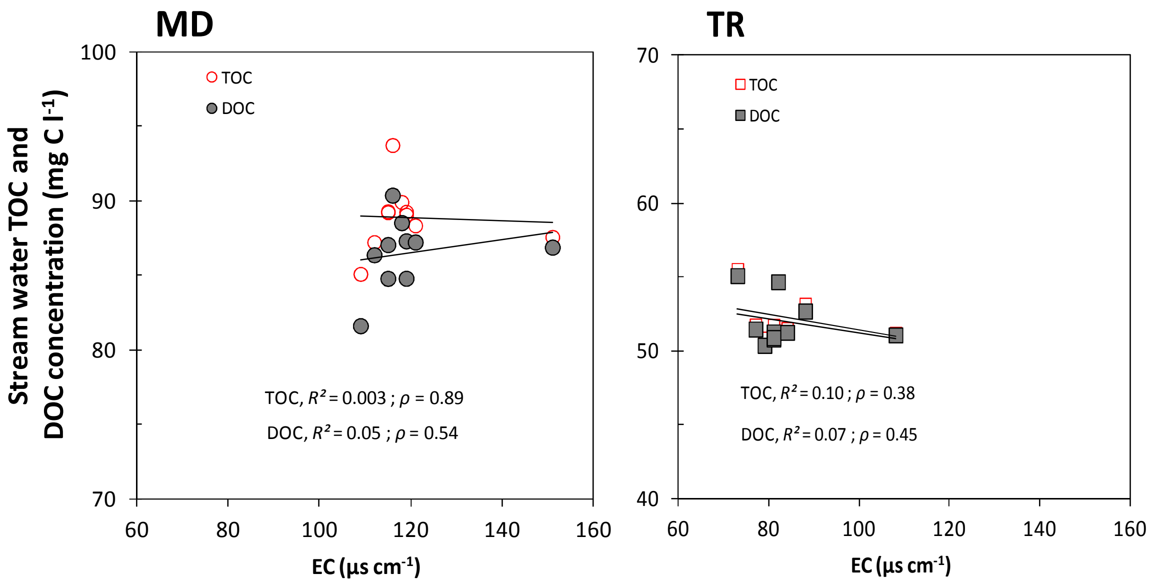


Figure 4.10 Relationship between EC and streamwater total organic carbon (TOC), dissolved organic carbon (DOC) concentrations in Meranti Ditch (MD) and Turip River (TR).

4.5 TOC, DOC and POC yield and load

Applying the catchment area estimates shown in Table 4.2, the TOC yield values were 41.6–55.5 g C m^{-2} yr^{-1} for MD and 26.2–34.9 g C m^{-2} yr^{-1} for TR (Table 3). The POC yields were very small, amounting to only 0.6–1.3 % of the TOC yields. The organic C yield (TOC, DOC and POC) was higher for MD than for TR. This is a reflection of the higher organic C concentration in MD.

The TOC load released from PSF to MD was calculated as 0.23 Gg C yr^{-1}, whereas the TOC load for TR was estimated at 14.0 Gg C yr^{-1} (Table 4.3). This value is based on a year (01 June 2012 to 31 May 2013) of continuous hydrological observations as shown in Figure 4.4 and Figure 4.5.

Table 4.3 also shows that there are significant differences between the organic C loads estimated using continuous and periodic data. TOC loads estimated using periodic data were 27 % higher than those estimated from continuous load for MD, and 8.8 % lower for TR. This was due to discharge variability during the monitoring period that could not be taken into account by the calculation using periodic data.

Table 4.3 Annual organic carbon (TOC, DOC and POC) yields and loads of Meranti Ditch (MD) and Turip River (TR) Calculated using continuous and periodic stream stage data for period 01 June 2012 to 31 May 2013. Yield = load / catchment area; * = upper estimate, ** = lower estimate (based on the lowest and highest estimates of the catchment area obtained using the water balance method, see Table 2). For loads calculated from periodic data, values in parentheses indicate the results as percentages of the corresponding loads calculated using continuous data.

site	property	data type		TOC	DOC	POC
MD	yield (Gg C m^{-2} yr^{-1})	continuous	*	55.5	54.8	0.7
			**	41.6	41.1	0.5
	load (Gg C yr^{-1})	continuous		0.233	0.230	0.003
		periodic		0.296 (127%)	0.287 (125%)	0.009 (200%)
TR	yield (Gg C m^{-2} yr^{-1})	continuous	*	34.9	34.7	0.2
			**	26.2	26.0	0.2
	load (Gg C yr^{-1})	continuous		14.0	13.9	0.1
		periodic		12.8 (91.2%)	12.7 (91.5%)	0.1 (58%)

4.6 Long-term apparent rates of carbon (C) accumulation (LARCA)

However, in TPSF C release through the atmosphere (C in form of CO_2) was 974.0–1,035.3 g C m^{-2} yr^{-1} (Hirano *et al*. 2009) and C release into stream water (C in form of TOC) was 41.6 to 55.5 g C m^{-2} yr^{-1} in the small MD catchment and from 26.2 to 34.9 in TR g C m^{-2} yr^{-1}. By comparing C release to the atmosphere and streamwater, C fluxes (release) gave the high values compared with C accumulation (LARCA) at MD and TR e.g., from 85.8 g C m^{-2} yr^{-1} to 112.6 g C m^{-2} yr^{-1}, while Page *et al* (2004) quantifying LARCA in tropical peat was 56 g C m^{-2} yr^{-1}, which does not include above ground biomass.

C store or C stock was obtained by multiplying of total peat carbon (C) with catchment area of study site MD and TR (Table 4.2). For MD C store or C stock was 0.002 Mt C whereas C store for TR was 0.24 Mt C. TR catchment have larger C stock than MD catchment due to TR catchment area larger than MD.

Chapter 5

DISCUSSION

There were significant differences in the estimates of organic C load that we obtained using continuous and periodic data. However, regardless of the calculation method, it was clear that almost all of the TOC contained in TPSF streamwater was in the form of DOC, with only 0.2–5.0 % occurring as POC. The TOC load transported from the TPSF catchment to the stream during the study period was estimated at 0.23 Gg C yr^{-1} for MD and 14.0 Gg C yr^{-1} for TR (Table 4.3).

Seasonal monitoring at these two sites showed that TOC and DOC concentrations in the stream were fairly stable and were not affected by the flow rate. The streamwater was acidic with pH in the range 3.4– 4.1 and an EC of 73–151 µs cm^{-1}, but the concentrations of TOC and DOC were not affected by variation in either these factors or discharge (flow rate). There was also no relationship between fluctuations of groundwater depth in the catchment and the concentrations of TOC and DOC in the stream. This invariability of C concentrations in TPSF water could be attributed to the intact condition of the TPSF and its consequently high organic C content, which enables it to provide a nearly constant supply of organic C to drainage water regardless of the rate at which water is moving through the system.

Stream TOC concentrations in MD (85–94 mg C L^{-1}) were higher than in TR (50–58 mg C L^{-1}). The high concentrations in MD are not surprising, as this catchment has been much disturbed by repeated rounds of logging which also involved the excavation of a dense network of ditches approximately ten years ago, with associated changes in peatland gradient and topography (subsidence). Under these conditions it seems likely that surface and subsurface water flow will readily flush peat C into streams. By comparison, TR has a large catchment of which 75 % is covered by intact TPSF, including a large peat plain headwater that has never been logged and, therefore, contributes less organic C to streamwater.

The average DOC concentrations in rainwater were 3.3 ±1.6 mg C L^{-1} at MD and 4.1±1.5 mg C L^{-1} at TR, and higher than in rainwater originating from other non-urban sites (Table 5.1). The DOC concentrations in our rainwater samples may have been influenced by haze from widespread burning of PSF in the drier months when most of the rainwater samples were collected (May–July 2012).

Table 5.1. DOC concentrations ((DOC), mg C L^{-1}) in rainwater of areas with different land uses/locations.

Type	Location	(DOC)	Reference
tropical PSF (MD)	Sumatra, Indonesia	3.30	this study
tropical PSF (TR)	Sumatra, Indonesia	4.10	this study
forest	Thailand	1.7	Möller *et al*. (2005)
	Taiwan	4.7	Liu & Sheu (2003)
Amazon Basin	Amazonia (Brasil)	0.82	Andrea *et al*. (1990)
	Amazonia (Brasil)	1.91	Williams *et al*. (1997)
rural	Hubbard Brook, New Hampshire, USA	1.09	Likens *et al*. (1983)
	New York, USA	1.92	Likens *et al*. (1983)
	The Netherlands	1.93	Nguyen *et al*. (1990)
urban	Tokyo	1.44	Sempéré & Kawamura (1994)
		7.44	
	Northern China	2.4–3.9	Yuepeng *et al*. (2010)
	Seoul, Korea	1.13	Yan & Kim (2012)
coastal	Puerto Rico	0.62	McDowell *et al*. (1990)
	Costa Rica	0.70	Eklund *et al*. (1997)
	Wilmington, North Carolina, USA	1.37	Willey et al. (2000)
	New Zealand	0.70	Kieber *et al*. (2002)
marine	Enewetak Atoll, Pacific Ocean, USA	1.18	Zafiriou *et al*. (1985)
		0.26	
	West Pacific, USA	1.50	Sempéré & Kawamura (1996)
	south New Zealand	0.29	Willey *et al*. (2000)

Table 5.2 gives DOC concentrations in streamwater from several locations and regions with a variety of catchment types, from this and previously published studies. The DOC concentration we recorded at MD was high compared to other sites. Several other TPSF locations also had high DOC concentrations.

Table 5.2 DOC concentrations ((DOC), mg C L^{-1}) in streamwater within different regions/catchment types.

		Location	Catchment Type	(DOC)	Reference
Indonesia	Riau Province	MD (Meranti ditch)	tropical PSF	82–90	this study
		TR (Turip River)	tropical PSF	49–57	this study
		Dumai River	tropical PSF and lowland forest	60.6	Alkhatib *et al.* (2007)
	central Sumatra	Tapung Kanan River	Oil palm and rubber estates, lowland forest and shrubs(53.4% peat area)	20.4–21.7	Baum *et al.* (2007)
		Tapung Kiri River	Oil palm and rubber estates, lowland forest and shrubs (3.9% peat area)	6.9–7.4	Baum *et al.* (2007)
		Mandau River	Oil palm and rubber estates, lowland forest and shrubs (48.1% peat area)	35.0–36.7	Baum *et al.* (2007)
	Central Kalimantan Province	Sebangau Forest	natural tropical PSF	62.0–64.1	Moore *et al.* (2013)
		Tumbang Nusa	disturbed tropical PSF	54.7–62.4	Moore *et al.* (2013)
		Kalampangan	disturbed tropical PSF	39.1–47.9	Moore *et al.* (2013)
		Taruna Main Canal	disturbed tropical PSF	32.4	Yupi & Inoue (unpublished data)
Malaysia	Penisular Malaysia	Oil palm channel draining (peatland)	Oil palm on peatland (Abandoned)	6	Moore *et al.* (2013)
		Oil palm channel draining (peatland)	Oil palm on peatland (Active)	13	Moore *et al.* (2013)
Japan	Hokkaido	Stream in Sarobetsu Mire	Natural boreal peatland	20	Takechi (2013)
Canada	Northern Manitoba	Sapochi River, East and West Basin Stream	Spruce, jack pine, palsa, fen and bog	15–30	Moore (2003)

Table 5.3 summarises DOC yields reported for different catchment types and regions, from this and previous studies. It is clear that TPSF has a high DOC yield compared to other catchment types in boreal and temperate regions. However, Baum *et al.* (2007) reported that oil palm and rubber estates in lowland

catchments had lower DOC yields than TPSF. It should be noted that the fraction of disturbed peat area in those catchments ranged from 3.9 to 53.4 %.

Table 5.3. DOC yields (g C m^{-2} yr^{-1}) from different catchment types and different regions.

Site	Catchment Type	DOC yield	Reference
Hubbard Brook, New Hampshire, USA	temperate deciduous forest	2	McDowell & Likens (1988)
Luquillo Mountains, Puerto Rico	tropical evergreen forest	3.25	McDowell (1998)
Troutbeck catchment, Moorhouse, UK	upland peat	4–7.4	Worall *et al.* (2006)
Maimai, Westland, New Zealand	temperate evergreen forest	6.8	Moore (1989)
Ochil Hills, Scotland	upland peat	8	Grieve (1984)
Mer Bleue bog, Ontario, Cananda	bog	8.3	Fraser *et al.* (2001)
Upper Hafren, Wales	upland peat	8.4	Dawson *et al.* (2002)
Sapochi River, East and West Basin Stream Manitoba Canada	spruce, jack pine, palsa, fen and bog	10–30	Moore (2003)
Loch Ard, Burn 11, Scotland	temperate evergreen forest	15	Grieve (1994)
Loch Ard, Burn 10, Scotland	temperate evergreen forest	16	Grieve (1994)
Brocky Burn, Scotland	upland peat	16.9	Dawson *et al.* (2002)
Larry River, Westland, New Zealand	wetland (moss/fern/scrub vegetation)	65.1	Moore & Jackson (1989)
Tapung Kanan River (Central Sumatra), Indonesia	oil palm and rubber estates, lowland forest and shrubs, (53.4% peat area)	4.9–41.1	Baum *et al.* (2007)
Tapung Kiri River (Central Sumatra), Indonesia	oil palm and rubber estates, lowland forest and shrubs, (3.9% peat area)	1.7–14.8	Baum *et al.* (2007)
Mandau River (Central Sumatra), Indonesia	oil palm and rubber estates, lowland forest and shrubs, (48.1% peat area)	9.1–70.4	Baum *et al.* (2007)
Sebangau River, Central Kalimantan Indonesia	natural tropical PSF	83	Moore *et al.* (2011)
Three channels in Sebangau forest, Central Kalimantan, Indonesia	natural tropical PSF	61.3	Moore *et al.* (2013)
Two channels in Tubangnusa, Central Kalimantan, Indonesia	disturbed tropical PSF, moderately drained	95.7	Moore *et al.* (2013)
Three channels in Kalampangan, Central Kalimantan, Indonesia	disturbed tropical PSF, severely drained	81.5	Moore *et al.* (2013)
Meranti Ditch (Riau, Central Sumatra) Indonesia	tropical PSF	41.1–54.8	this study
Turip River (Riau, Central Sumatra) Indonesia	tropical PSF	26.0–34.7	this study

In our study, TOC yields ranged from 41.6 to 55.5 g C m^{-2} yr^{-1} in the small (4.8 km^2) MD catchment and from 26.2 to 34.9 g C m^{-2} yr^{-1} in the larger (458 km^2) TR catchment. This result matches the findings of Dawson *et al*. (2004), who report that smaller catchments in C-rich landscapes typically have higher C yields or fluxes than similar but larger catchments. The quantities of organic C discharged by the MD and TR streams, *per* unit area of TPSF, were only 2.7–5.4 % of current estimates of the total amount of C released to the atmosphere from TPSF,e.g.974.0–1,035.3 g C m^{-2} yr^{-1} (Hirano *et al*. 2009) as shown on Figure 5.1. Our result of relatively small amounts of C being released through streamwater is relevant to improving estimates of the TPSF C budget, as well as to our understanding of how C is transferred between PSF and the hydrosphere.

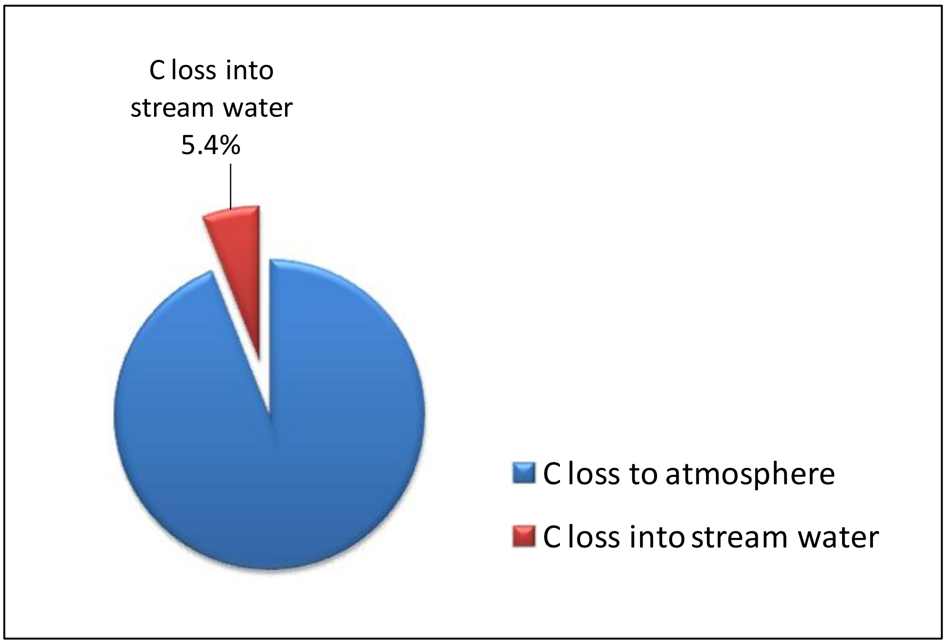


Figure 5.1 Comparison of C loss from tropical PSF to the atmosphere and C loss into the stream.

Chapter 6

CONCLUSIONS

It was clear that the greatest portion of TPSF stream water TOC was in the form of DOC and only a small portion was in the form of POC (0.2 to 5.0 % of TOC). TOC load transported from the TPSF catchment to the stream during the study period was estimated as 0.23 Gg C yr^{-1} for MD and 14.0 Gg C yr^{-1} for TR. There were significant differences in organic C load estimation between continuous and periodic data. Through seasonal monitoring at two sites, we found that TOC and DOC concentrations in the stream were fairly stable and were not affected by the flow rate. Stream water was acidic with pH in a range of 3.4 to 4.1, and EC in a range of 73 to 151 μs cm^{-1}, however the TOC and DOC concentrations were not affected by variation in either this factors. Fluctuations of groundwater depth in the catchment had no relationship with concentrations of TOC and DOC it streamwater.

Stream TOC concentrations in MD were higher than in TR due to this catchment has been much disturbed by repeated rounds of logging which also involved the excavation of a dense network of ditches approximately ten years ago, with associated changes in topography and peat land gradient, it seems likely that surface and subsurface water flow will readily flushed the peat C to the stream. Compare with TR catchment which has intact area of TPSF, including a large peat plain headwater that has never been logged, contribute less organic C to streamwater.

Summarises DOC yields reported for different catchment types and regions, from this and previous studies, it was clear that TPSF has a high DOC yield compared to other catchment types in boreal and temperate regions.

In our study, TOC yields ranged of 41.6–55.5 g C m^{-2} yr^{-1} in the small MD catchment and 26.2–34.9 g C m^{-2} yr^{-1} in the larger TR catchment. This result matches the findings of Dawson *et al*. (2004), who report that smaller catchments in C-rich landscapes typically have higher C yields or fluxes. Relative to total C released from TPSF to the atmosphere according to some estimates, e.g., 974.0 to 1,035.3 g C m^{-2} yr^{-1} (Hirano *et al*. 2009), the released organic C yields through MD and TR stream water relatively small amount (from 2.7 to 5.4%).

ABSTRACT

Study on stream water discharge and organic carbon concentrations, loads and yields of tropical peat swamp forest of Riau, Sumatra, Indonesia

（インドネシア国スマトラ島リアウ州の熱帯泥炭湿地林における河川流出と有機態炭素流出に関する研究）

Approximately 11 % (4.41 × 105 km^2) of the global area of peatland lies within the tropics. Of this, 56 % (approximately 2.48 × 105 km^2) is located in Southeast Asia, mostly in Indonesia and Malaysia. The 88.6 GT of carbon (C) stored in tropical peat accounts for 11–14 % of the global peat C store, and Southeast Asia's peat deposits are estimated to contain 77 % (68.5 Gt) of this. The largest accumulations of tropical peat C are in Indonesia (57.4 Gt C, i.e. 65 % of the total C in tropical peat) and Malaysia (9.1 Gt, 10 %). Tropical peat swamp forest (PSF) is formed when organic matter accumulates as a peat layer. It has important roles in regulating water movement, the hydrological cycle, C storage and the regional and global C cycles. When affected by human activities, the organic C pool in peatlands can potentially release large amounts of C into the environment as gaseous emissions and waterborne (fluvial) losses.

Organic C is released from peatlands in substantial amounts and waterborne C may constitute a substantial part of the peatland C balance, as reported for boreal peatland. Carbon is released into watercourses in both organic and inorganic forms and partly as free (gaseous) CO_2 and CH_4. Organic forms include dissolved organic carbon (DOC) and particulate organic carbon (POC). It is well known that the water in tropical peatland rivers has very high DOC concentrations and lower POC concentrations.

Despite increasing interest in C release via PSF river systems, few studies have been conducted. To improve accuracy and to clarify how discharge variability influences the organic C load in PSF watercourses, it is necessary to have continuous measurements of water discharge. This is because both rainfall events and discharge responses affect the rate of flow in streams and rivers. Periodic measurements of stream discharge combined with continuous recording of stream water level (stage) can provide accurate continuous flow rate data if the rating curve (i.e. a graph of discharge versus stage) is available.

The purpose of this study was to quantify the C loads of watercourses draining from PSF in Riau Province, Sumatra, Indonesia, by combining continuous flow data with measurements of organic C concentration in the water, and thus to estimate catchment yields of organic C. This study also compares results obtained using continuous measurements of organic C load with those that would be indicated by periodic measurements.

Two watercourses were selected for hydrological measurements. One is a small artificial stream named Meranti Ditch (MD) and the other is Turip River (TR). There were significant differences in the estimates of organic C load that obtained using continuous and periodic data. However, regardless of the calculation method, it was clear that almost all of the TOC contained in PSF streamwater was in the form of DOC, with only 0.2–5.0 % occurring as POC. The TOC load transported from the PSF catchment to the stream during the study period was estimated at 0.23 Gg C yr^{-1} for MD and 14.0 Gg C yr^{-1} for TR. Seasonal monitoring at these two sites showed that TOC and DOC concentrations in the stream were fairly stable and were not affected by the flow rate. The streamwater was acidic with pH in the range 3.4 – 4.1 and an EC of 73 – 151 µs cm^{-1}, but the concentrations of TOC and DOC were not affected by variation in either these factors or discharge. There was also no relationship between fluctuations of groundwater depth in the catchment and the concentrations of TOC and DOC in the stream. This invariability of C concentrations in PSF water could be attributed to the intact condition of the PSF and its consequently high organic C content, which enables it to provide a nearly constant supply of organic C to drainage water regardless of the rate at which water is moving through the system.

Stream TOC concentrations in MD (85 – 94 mg C L^{-1}) were higher than in TR (50 – 58 mg C L^{-1}). The high concentrations in MD are not surprising, as this catchment has been much disturbed by repeated rounds of logging which also involved the excavation of a dense network of ditches approximately ten years ago, with associated changes in peatland gradient and topography (subsidence). Under these conditions it seems likely that surface and subsurface water flow will readily flush peat C into streams. By comparison, TR has a large catchment of which 75 % is covered by intact PSF, including a large peat plain headwater that has never been logged and, therefore, contributes less organic C to streamwater.

From the comparison between this study and previously published studies of DOC concentrations in streamwater from several locations and regions with a variety of catchment types, the DOC concentration recorded at MD was high compared to other sites. Several other PSF locations also had high DOC concentrations. Also from the summaries of DOC yields reported for different catchment types and regions, it is clear that PSF has a high DOC yield compared to other catchment types in boreal and temperate regions.

In this study, TOC yields ranged from 41.6 to 55.5 g C m^{-2} yr^{-1} in the small (4.8 km^2) MD catchment and from 26.2 to 34.9 g C m^{-2} yr^{-1} in the larger (458 km^2) TR catchment. This result matches the findings of previous study, which reported that smaller catchments in C-rich landscapes typically have higher C yields or fluxes than similar but larger catchments. The quantities of organic C discharged by the MD and TR streams, *per* unit area of PSF, were only 2.7 – 5.4 % of current estimates of the total amount of C released to the atmosphere from PSF, e.g., 974.0 – 1,035.3 g C m^{-2} yr^{-1}. Our report of relatively small amounts of C being released through streamwater is relevant to improving estimates of the C budget of PSF, as well as to our understanding of how C is transferred between PSF and the hydrosphere.

APPENDIX:

I). STATISTICAL ANALYSIS,

Relationship between stream Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC) with some parameter i.e., stream discharge (Q), ground water depth (GWD), PH and Electric conductivity (EC) in Meranti Ditch (MD) and Turip River (TR)

II). FLOWCHART:

- **Flowchart (general)**
- **Detail Flowchart (main data groups used)**
- **Detail Flowchart (the step difference between periodic estimation and continuous estimation)**

Statistic analysis using ANOVA
Relationship between stream TOC concentration and discharge (Q) in MD

Regression Statistics	
Multiple R	0.44
R Square	0.2
Adjusted R Square	0.11
Standard Error	1.95
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*p*
Regression	1	9.21	9.21	2.42	0.15
Residual	10	38.01	3.80		
Total	11	47.22			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	87.18	1.10	78.92	0.00	84.72	89.65	84.72	89.65
X Variable 1	15.40	9.89	1.56	0.15	-6.65	37.44	-6.65	37.44

Statistic analysis using ANOVA

Relationship between stream DOC concentration and discharge (Q) in MD

Regression Statistics	
Multiple R	0.40
R Square	0.16
Adjusted R Square	0.07
Standard Error	2.08
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*ρ*
Regression	1	8.09	8.09	1.86	0.20
Residual	10	43.44	4.34		
Total	11	51.52			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	85.26	1.18	72.19	0.00	82.62	87.89	82.62	87.89
X Variable 1	14.43	10.58	1.36	0.20	-9.14	37.99	-9.14	37.99

Statistic analysis using ANOVA

Relationship between stream TOC concentration and discharge (Q) in TR

Regression Statistics	
Multiple R	0.30
R Square	0.09
Adjusted R Square	-0.002
Standard Error	1.45
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*ρ*
Regression	1	2.06	2.06	0.98	0.35
Residual	10	21.03	2.10		
Total	11	23.09			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	51.30	1.34	38.30	0.00	48.32	54.29	48.32	54.29
X Variable 1	0.17	0.17	0.99	0.35	-0.22	0.56	-0.22	0.56

Statistic analysis using ANOVA
Relationship between stream DOC concentration and discharge (Q) in TR

Regression Statistics	
Multiple R	0.21
R Square	0.05
Adjusted R Square	-0.05
Standard Error	1.54
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*p*
Regression	1	1.12	1.12	0.48	0.51
Residual	10	23.61	2.36		
Total	11	24.73			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	51.26	1.42	36.11	0.00	48.09	54.42	48.09	54.42
X Variable 1	0.13	0.18	0.69	0.51	-0.28	0.54	-0.28	0.54

Statistic analysis using ANOVA

Relationship between stream TOC concentration and Ground water depth (GWD) in MD

Regression Statistics	
Multiple R	0.23
R Square	0.05
Adjusted R Square	-0.05
Standard Error	2.22
Observations	11

ANOVA

	df	*SS*	*MS*	*F*	*ρ*
Regression	1	2.55	2.55	0.52	0.49
Residual	9	44.31	4.92		
Total	10	46.86			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	89.95	1.98	45.44	0.00	85.47	94.43	85.47	94.43
X Variable 1	5.07	7.04	0.72	0.49	-10.86	20.99	-10.86	20.99

Statistic analysis using ANOVA

Relationship between stream DOC concentration and Ground water depth (GWD) in MD

Regression Statistics	
Multiple R	0.062
R Square	0.004
Adjusted R Square	-0.107
Standard Error	2.301
Observations	11

ANOVA

	df	*SS*	*MS*	*F*	*ρ*
Regression	1	0.187	0.187	0.035	0.86
Residual	9	47.668	5.296		
Total	10	47.855			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	87.172	2.053	42.457	0.000	82.527	91.816	82.527	91.816
X Variable 1	1.370	7.302	0.188	0.855	-15.148	17.888	-15.148	17.888

Statistic analysis using ANOVA

Relationship between stream TOC concentration and Ground water depth (GWD) in TR

Regression Statistics	
Multiple R	0.21
R Square	0.04
Adjusted R Square	-0.02
Standard Error	2.07
Observations	17

ANOVA

	df	*SS*	*MS*	*F*	*ρ*
Regression	1	2.94	2.94	0.69	0.42
Residual	15	64.25	4.28		
Total	16	67.19			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	52.66	0.50	104.55	0.00	51.59	53.73	51.59	53.73
X Variable 1	2.31	2.78	0.83	0.42	-3.63	8.24	-3.63	8.24

Statistic analysis using ANOVA

Relationship between stream DOC concentration and Ground water depth (GWD) in TR

Regression Statistics	
Multiple R	0.061
R Square	0.003
Adjusted R Square	-0.063
Standard Error	2.102
Observations	17

ANOVA

	df	*SS*	*MS*	*F*	*p*
Regression	1	0.248	0.248	0.056	0.82
Residual	15	66.264	4.418		
Total	16	66.513			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	52.141	0.512	101.932	0.000	51.050	53.231	51.050	53.231
X Variable 1	0.670	2.827	0.237	0.816	-5.356	6.696	-5.356	6.696

Statistic analysis using ANOVA

Relationship between stream TOC concentration and pH in MD

Regression Statistics	
Multiple R	0.086
R Square	0.007
Adjusted R Square	-0.117
Standard Error	2.339
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*ρ*
Regression	1	0.326	0.326	0.060	0.81
Residual	8	43.773	5.472		
Total	9	44.099			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	93.419	18.574	5.029	0.001	50.586	136.251	50.586	136.251
X Variable 1	-1.215	4.976	-0.244	0.813	-12.689	10.260	-12.689	10.260

Statistic analysis using ANOVA

Relationship between stream DOC concentration and pH in MD

Regression Statistics	
Multiple R	0.21
R Square	0.04
Adjusted R Square	-0.08
Standard Error	2.45
Observations	10.00

ANOVA

	df	*SS*	*MS*	*F*	*p*
Regression	1	2.18	2.18	0.36	0.56
Residual	8	48.21	6.03		
Total	9	50.39			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	98.24	19.49	5.04	0.00	53.29	143.19	53.29	143.19
X Variable 1	-3.14	5.22	-0.60	0.56	-15.18	8.90	-15.18	8.90

Statistic analysis using ANOVA
Relationship between stream TOC concentration and pH in TR

Regression Statistics	
Multiple R	0.28
R Square	0.08
Adjusted R Square	-0.04
Standard Error	1.66
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*p*
Regression	1	1.85	1.85	0.67	0.44
Residual	8	22.02	2.75		
Total	9	23.87			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	33.71	22.67	1.49	0.18	-18.57	86.00	-18.57	86.00
X Variable 1	4.69	5.72	0.82	0.44	-8.51	17.89	-8.51	17.89

Statistic analysis using ANOVA

Relationship between stream DOC concentration and pH in TR

Regression Statistics	
Multiple R	0.28
R Square	0.08
Adjusted R Square	-0.04
Standard Error	1.69
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*ρ*
Regression	1	1.89	1.89	0.67	0.44
Residual	8	22.76	2.84		
Total	9	24.65			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	33.19	23.05	1.44	0.19	-19.97	86.34	-19.97	86.34
X Variable 1	4.75	5.82	0.82	0.44	-8.67	18.17	-8.67	18.17

Statistic analysis using ANOVA

Relationship between stream TOC concentration and EC in MD

Regression Statistics	
Multiple R	0.052
R Square	0.003
Adjusted R Square	-0.122
Standard Error	2.345
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*ρ*
Regression	1	0.118	0.118	0.021	0.89
Residual	8	44.007	5.501		
Total	9	44.125			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	90.065	8.070	11.161	0.000	71.456	108.674	71.456	108.674
X Variable 1	-0.010	0.067	-0.147	0.887	-0.165	0.145	-0.165	0.145

Statistic analysis using ANOVA

Relationship between stream DOC concentration and EC in MD

Regression Statistics	
Multiple R	0.22
R Square	0.05
Adjusted R Square	-0.07
Standard Error	2.45
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*ρ*
Regression	1	2.43	2.43	0.41	0.54
Residual	8	47.95	5.99		
Total	9	50.39			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	81.17	8.42	9.64	0.00	61.74	100.59	61.74	100.59
X Variable 1	0.04	0.07	0.64	0.54	-0.12	0.21	-0.12	0.21

Statistic analysis using ANOVA

Relationship between stream TOC concentration and EC in TR

Regression Statistics	
Multiple R	0.31
R Square	0.10
Adjusted R Square	-0.01
Standard Error	1.64
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*p*
Regression	1	2.34	2.34	0.87	0.38
Residual	8	21.50	2.69		
Total	9	23.83			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	56.77	4.82	11.78	0.00	45.66	67.88	45.66	67.88
X Variable 1	-0.05	0.06	-0.93	0.38	-0.19	0.08	-0.19	0.08

Statistic analysis using ANOVA

Relationship between stream DOC concentration and EC in TR

Regression Statistics	
Multiple R	0.27
R Square	0.07
Adjusted R Square	-0.04
Standard Error	1.69
Observations	10

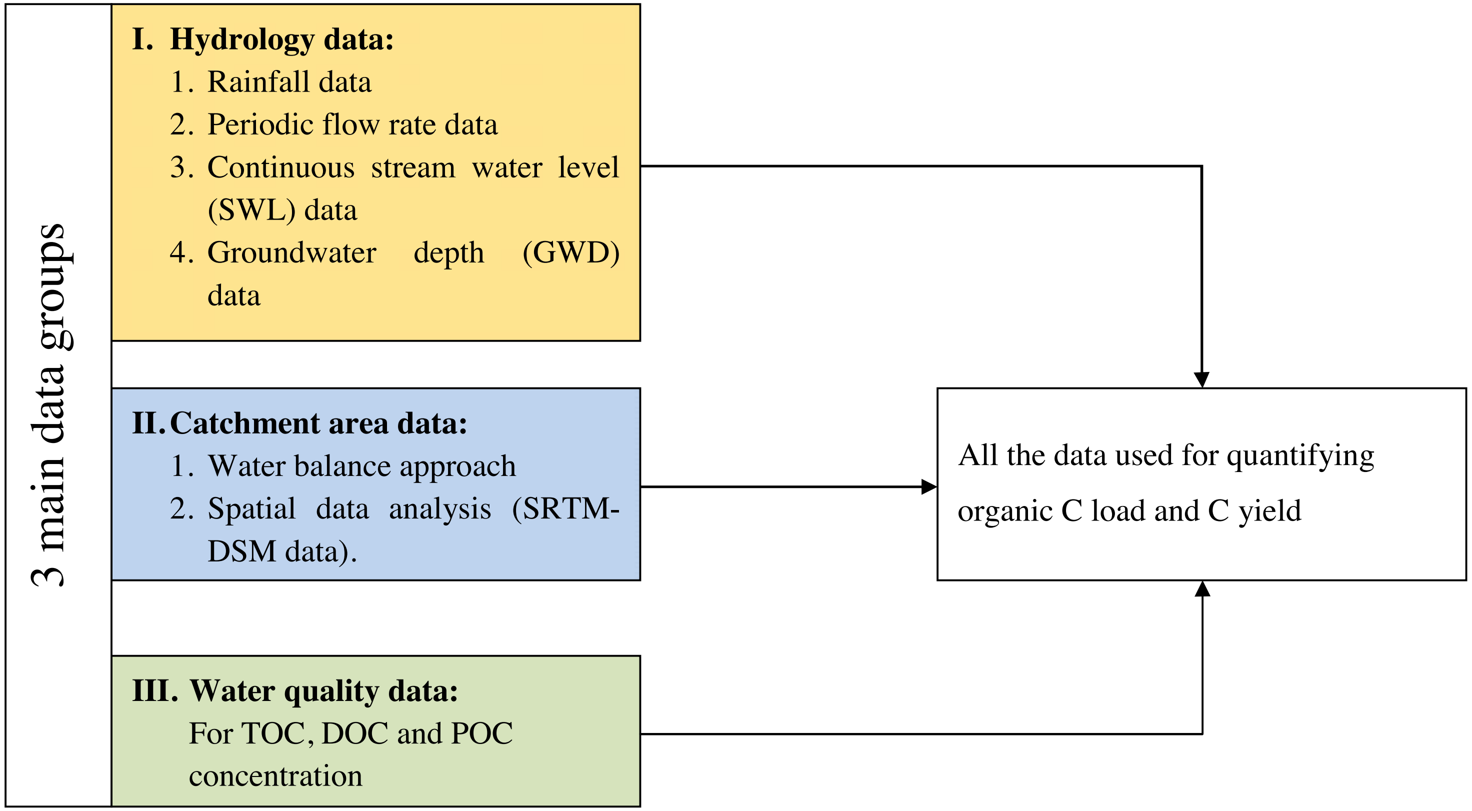
ANOVA

	df	*SS*	*MS*	*F*	*ρ*
Regression	1	1.78	1.78	0.62	0.45
Residual	8	22.87	2.86		
Total	9	24.65			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	55.88	4.97	11.24	0.00	44.42	67.34	44.42	67.34
X Variable 1	-0.05	0.06	-0.79	0.45	-0.18	0.09	-0.18	0.09

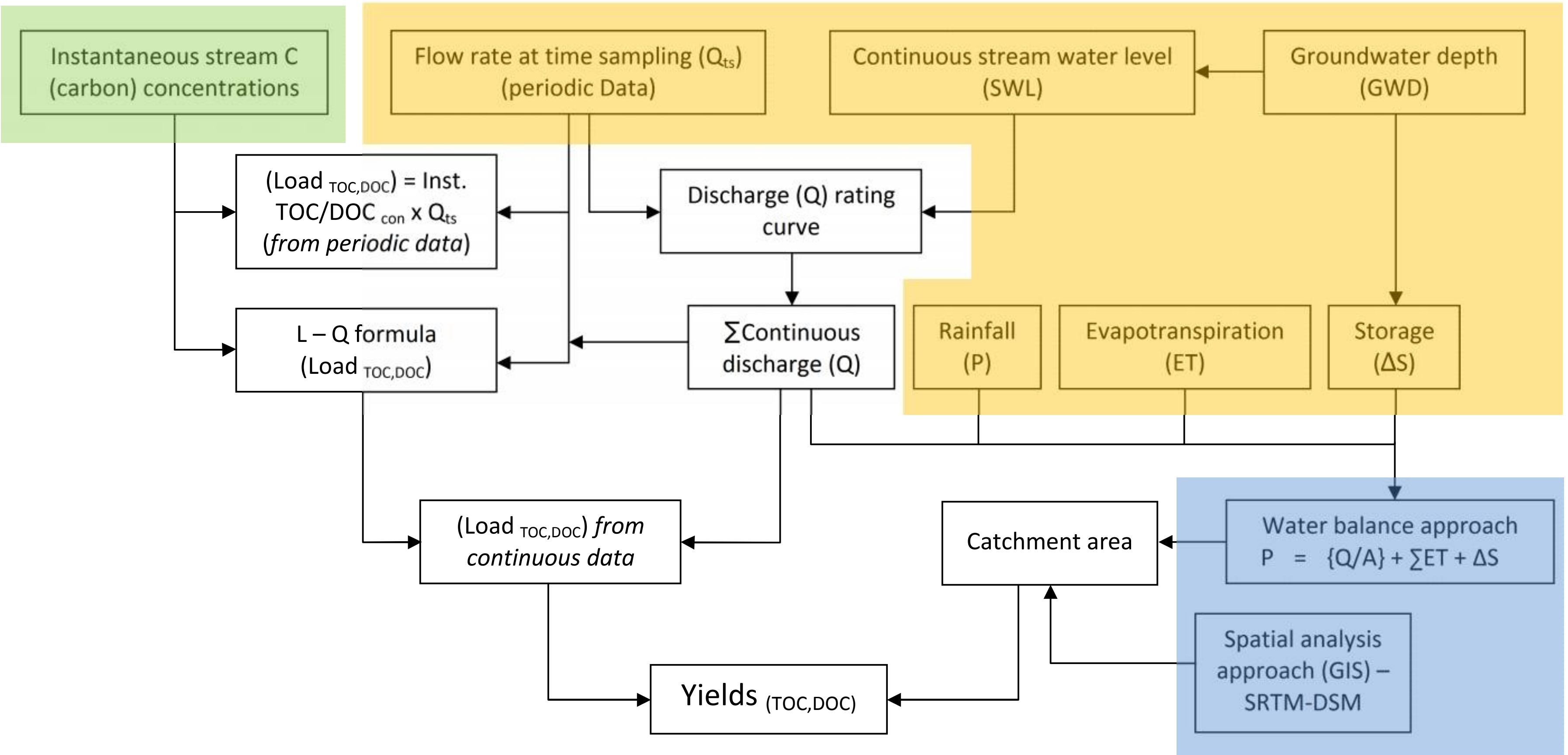
II). FLOWCHART:

- **Flowchart (general)**



II). FLOWCHART

– **Detail Flowchart (The main data groups used)**



3 MAIN DATA GROUP

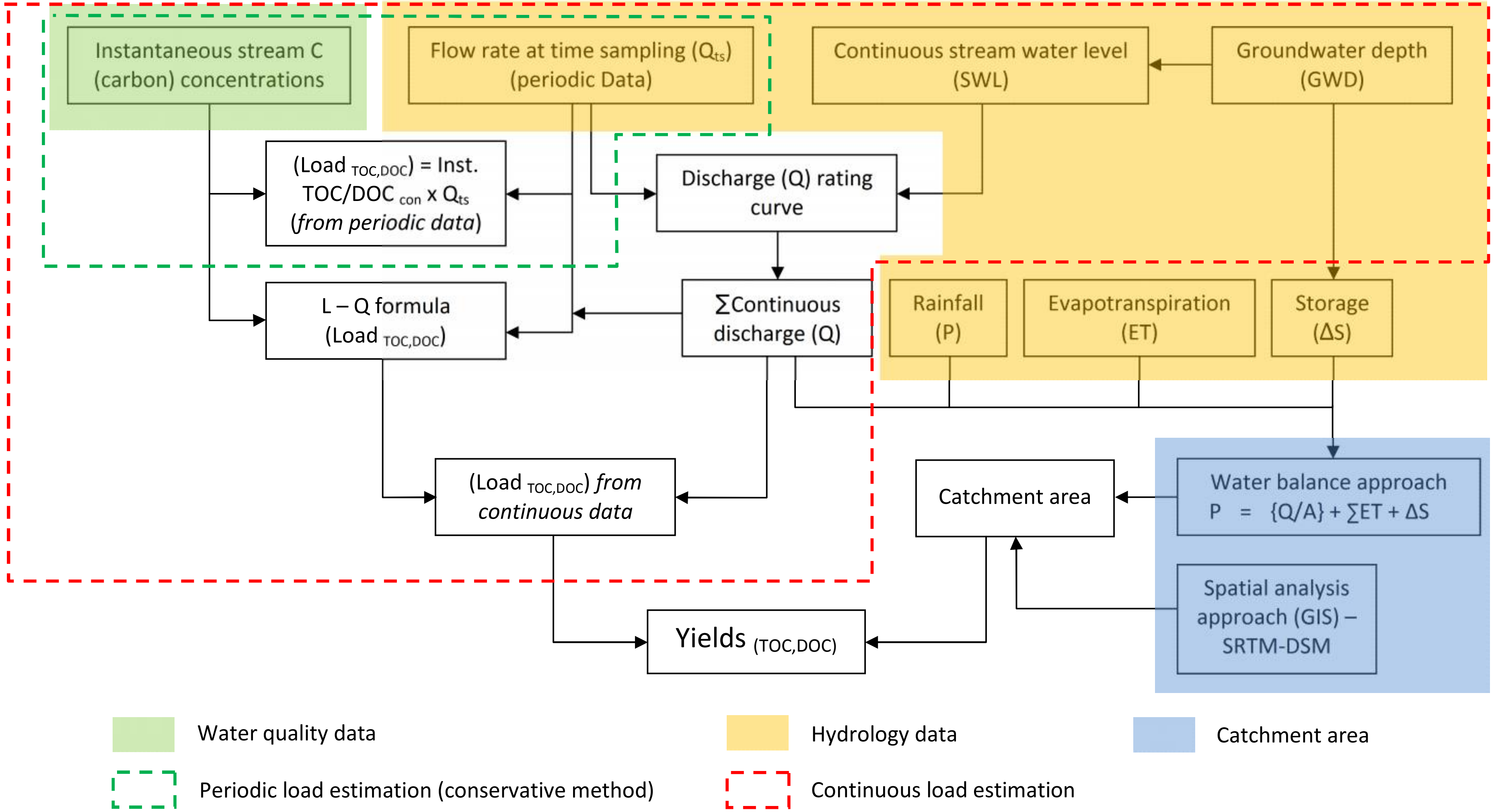
Water quality data

Hydrology data

Catchment area

II). FLOWCHART

– **Detail Flowchart (The step difference between periodic estimation and continuous estimation)**



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