Carbon Cycling in Tropical Rivers: A Carbon Isotope Reconnaissance Study of the Langat and Kelantan Basins, Malaysia

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ABSTRACT

Despite the importance of tropical rivers to the global carbon cycle, the nature of carbon cycling within these watersheds has been dealt with by only a handful of studies. The current work attempts to address this lack of information, using stable isotope and concentration measurements to constrain sources and sinks of carbon in two Peninsular Malaysian watersheds. The basins are located on the central-western and northeastern coasts of the Malaysian Peninsula, and are drained by the Langat and Kelantan Rivers, respectively. Water samples were collected from three points along the two rivers twice a month, in addition to the sampling of groundwater in adjacent aquifers.

Principal component analyses (PCA) on water chemistry parameters in the Langat and Kelantan Rivers show the dominance of geogenic and anthropogenic influences, grouped in 4 to 6 components that comprise over 50 % of the total dataset variances. The geogenic input is reflected by components showing strong loadings by Ca, Mg, Mn, Si, and Sr, while anthropogenic influences via pollution are indicated via strong loadings by NO_3, SO_4, K, Zn and Cl. The carbon isotope and concentration data appear unrelated to these groups, suggesting that the riverine carbon cycle in both locations is dominated by other factors. These may include alternative sources of organic pollution, or inputs from the local vegetation and soils.

The mean riverine $\delta^{13}C_{DOC}$ of -27.8 ± 2.9 ‰ and -26.6 ± 2.2 ‰ in the Langat and Kelantan Basins, respectively, are consistent with the dominance of C3-type vegetation in both watersheds. Riverine $\delta^{13}C_{DIC}$ signatures approach C3-like values at high DIC concentrations, with measurements as low as -19 ‰ in the Kelantan Basin and -20 ‰ observed in the Langat Basin, consistent with a biological origin for riverine DIC. However, the average $\delta^{13}C_{DIC}$ in river

water is ^{13}C-enriched by about 10 ‰ relative to the expected C3 source in both rivers, and this ^{13}C- enrichment appears to be largest with smaller DIC concentrations.

Because of the overpressures of CO_2 in the rivers, entrainment of isotopically-heavy atmospheric CO_2 is not a likely explanation for the observed ^{13}C-enrichment. Theoretically, dissolution of carbonates could be an alternative source of ^{13}C-enriched carbon, but this lithology is scarce, particularly in the Langat watershed. The increase in DIC downstream and generally high pCO_2 values in most river sections argues against aquatic photosynthesis as a primary causative factor for the observed isotopic enrichment. This elimination process leaves the speciation of riverine DIC and the evasion of CO_2 as the most likely mechanisms for ^{13}C-enrichment in DIC, via isotope fractionation during HCO_3^- hydration and CO_2 diffusion. Potentially, methanogenic activity could also be, at least partially, responsible for the ^{13}C-enrichment in DIC, particularly immediately downstream of the Langat Reservoir, but due to the absence of empirical data, this must remain only a theoretical proposition.

The aquatic chemistry and dissolved carbon data suggests that pollution discharge into the Langat and Kelantan Rivers is the major factor that is responsible for the considerable CO_2 overpressures and high DIC and DOC concentrations in the river waters, particularly in the downstream sections. This pollution is likely of biological origin, via sewage and palm oil mill effluent (POME) discharge, and therefore isotopically indistinguishable from natural C3 plant sources.

Carbon budgets of the Langat and Kelantan River show CO_2 degassing to be a significant mechanism of fluvial carbon loss, comprising roughly 50 %, or more, of the total riverine carbon export in both watersheds. The remainder of the river carbon is transported to the ocean in the form of DIC, DOC and POC in broadly comparable proportions. However, the combined riverine carbon export from the Kelantan and Langat Basins amount to 2 % or less of the total carbon sequestration of the watersheds. Thus, most of the sequestered carbon is returned to the atmosphere via respiration, with smaller amounts incorporated into ecosystem biomass.

These results highlight the complexity of carbon cycling in tropical rivers, and agree with previous studies in showing riverine systems to be more than simple conduits of carbon from the land to the ocean.

RÉSUMÉ

La nature du cycle du carbone dans les régions tropicales a été traitée par un petit nombre d'études. Cette étude tente de clarifier ce sujet en utilisant des isotopes stables du carbone et les concentrations des éléments afin de déterminer les sources et les puits de carbone dans les deux bassins versants de la péninsule malaisienne. Les bassins versants étudiés sont ceux de la rivière Langat, sur la côte centre-ouest de la péninsule, et de la rivière Kelantan, dans le nord-est. Des échantillons d'eau ont été prélevés bimensuellement sur trois sites le long des deux rivières. Un échantillonnage des eaux souterraines des aquifères adjacents a également eu lieu.

L'analyse en composantes principales (ACP) des paramètres chimiques de l'eau a montré la prédominance des influences géogéniques et anthropiques, qui ont été regroupées en 4 ou 5 facteurs composant plus de 50% de la variance de données. Les influences géogéniques sont indiquées par des paramètres qui montrent des poids forts en Ca, Mg, Mn, Si et Sr, tandis que les influences anthropiques polluantes sont indiquées par des poids forts de NO_3, SO_4, K, Zn et Cl. Les ratios isotopiques et les concentrations de carbone ne semblent pas être corrélés avec les paramètres précédemment énumérés, ce qui suggère que les cycles du carbone dans les deux bassins fluviaux sont dominés par d'autres facteurs. Ceux-ci peuvent inclure d'autres sources de pollution organique via la végétation et les sols locaux, par exemple.

Le $\delta^{13}C_{DOC}$ fluvial moyen de -27,8 ± 2,9 ‰ et de -26,6 ± 2,2 ‰ dans les bassins Langat et Kelantan respectivement, sont compatibles avec la domination de la végétation C3 dans les deux bassins versants. Les valeurs de $\delta^{13}C_{DIC}$ riveraines approchent celles des plantes C3, accompagnées de concentrations élevées de DIC. Les valeurs aussi basses que -19 ‰ dans le bassin de Kelantan et -20 ‰ dans le bassin Langat, montrent une compatibilité avec une origine

biologique pour la DIC riveraine. Cependant, la valeur moyenne de $\delta^{13}C_{DIC}$ dans l'eau de la rivière est enrichie d'environ 10 ‰ par rapport aux végétaux C3, source importante de carbone dans les deux rivières. Cet enrichissement semble être plus grand avec des concentrations de DIC plus faibles.

En raison des fortes concentrations de CO_2 dans les rivières, l'entraînement de CO_2 atmosphérique des isotopes lourds n'est pas une explication probable de l'enrichissement du ^{13}C observé. Théoriquement, la dissolution des carbonates pourrait être une autre source de carbone-13, mais la lithologie carbonate est rare dans le bassin versant Langat. L'augmentation de la DIC en aval, avec des valeurs élevées de pCO_2 dans la plupart des sites de la rivière, montrent que la photosynthèse aquatique ne peut constituer une cause principale de l'enrichissement isotopique. Cela laisse la spéciation de la DIC riveraine et l'évasion de CO_2 comme les mécanismes les plus probables pour l'enrichissement du ^{13}C de la DIC, par fractionnement isotopique lors de l'hydratation du HCO_3 et la diffusion du CO_2. Potentiellement, l'activité méthanogène peut aussi être, au moins partiellement, responsable de l'enrichissement en ^{13}C de la DIC, en particulier immédiatement en aval du réservoir Langat. En raison de l'absence de données empiriques, cela doit rester une proposition théorique.

La chimie aquatique et les données de carbone dissous suggèrent que la décharge de la pollution dans les rivières Langat et Kelantan est le principal facteur responsable des concentrations considérables de CO_2 et des valeurs élevées de DIC et DOC dans les eaux de la rivière, en particulier dans les sections en aval. Cette pollution est probablement d'origine biologique, par l'intermédiaire des eaux usées et des décharge de l'huilerie de la palmeraie, et donc isotopiquement indiscernable de sources végétales C3.

Les bilans du carbone de la Langat et Kelantan rivière montrent que le dégazage de CO_2 peut être un mécanisme important dans la perte de carbone fluvial, comprenant environ 50%, ou plus, de l'exportation de carbone riverain total dans les deux bassins versants. Le reste du carbone de la rivière est transporté à l'océan sous la forme de DIC, DOC et POC dans des proportions largement comparables. Cependant, l'exportation de carbone fluvial combinée des bassins Kelantan et Langat sont de 2% ou moins de la séquestration totale de carbone des bassins versants.

Ainsi, la majeure partie du carbone fixé est renvoyé à l'atmosphère par la respiration biologique, avec de plus petites quantités incorporées dans la biomasse de l'écosystème. Ces résultats mettent en évidence la complexité du cycle du carbone dans les rivières tropicales, et sont en accord avec des études antérieures montrant que les systèmes fluviaux sont plus que de simples conduits de carbone reliant le sol à l'océan.

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1.0 INTRODUCTION AND BACKGROUND

1.1 The Global Carbon Cycle and Tropical Rivers

The nature of carbon cycling in tropical watersheds remains poorly clarified. Few studies have addressed the contributions of tropical rivers to the global carbon cycle, and the resulting influences on worldwide climate. This is a subject of importance, given that tropical rivers provide more than 50 % of the global water discharge, and therefore the largest percentage of the total fluvial carbon flux to the oceans (Meybeck, 1993). As well, the intensive land-use changes occurring in tropical regions warrant additional study, as anthropogenic effects on riverine carbon cycling are generally not well known.

The global carbon cycle has traditionally been presented as a number of reservoirs linked by transfer pathways. Namely the atmosphere, terrestrial biomass, soil, the ocean and its associated biota, and the lithosphere have been identified as primary carbon repositories (Mackenzie and Lerman, 2006). Carbon is exchanged between these 4 components via a series of links, which constitute the carbon cycle as a whole. In the past, rivers have been viewed as one of these links, connecting terrestrial environments to the ocean.

However, carbon within rivers can be subjected to numerous processes in situ. These include production and consumption by biological processes, inputs via mineral weathering of adjacent bedrock, atmosphere-water exchange of CO_2, and outgassing of CO_2 and CH_4 (Hope et al., 1994; de Angelis and Lilley, 1987) (fig. 1). Thus, rivers should be considered as active components of the carbon cycle, rather than simply passive agents of transportation. This gives rivers and streams a more complex role in global carbon cycling, and one that merits additional research.

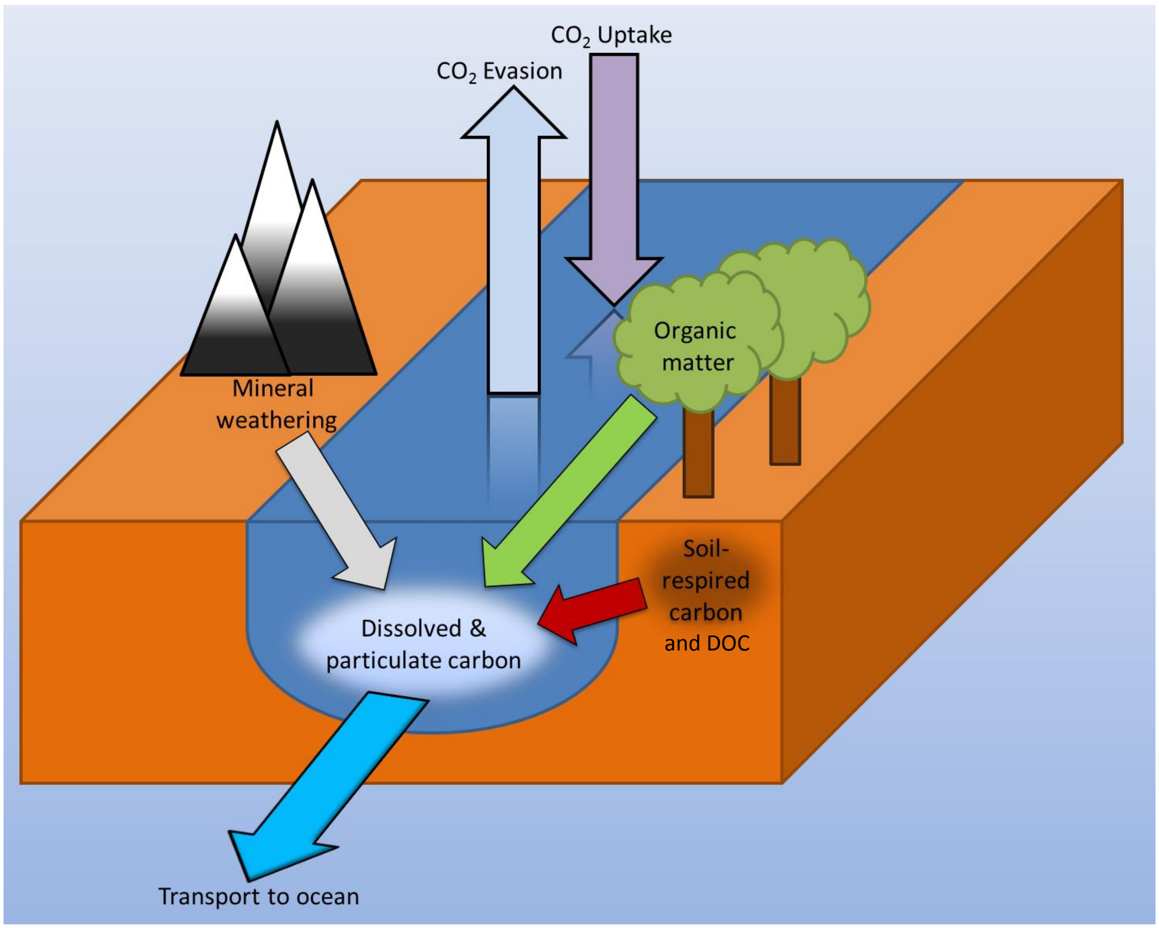


Figure 1: Simplified schematic of riverine carbon cycling, showing major natural fluxes.

1.2 Carbon in Riverine Environments

Riverine carbon can be organic or inorganic in origin, and are present in particulate and dissolved forms ("dissolved" typically being defined as material which can pass through a 0.45 μm pore filter). Dissolved inorganic carbon (DIC) can be derived from carbonate rocks, soil carbon or atmospheric CO_2. This carbon can enter rivers via mineral and soil weathering, as well as by diffusion of gaseous CO_2 directly into the water. DIC derived from rock weathering is mostly present in the form of bicarbonate ions (HCO_3^-) within the most common river pH range (~7), which can be formed by any one, or both, of the following reactions (Meybeck, 1993):

(1) Non-carbonate mineral + CO_2 + H_2O → HCO_3^- + clay mineral + cation + SiO_2

(2) Carbonate mineral + CO_2 + H_2O → $2HCO_3^-$ + Ca^{2+} (and/or Mg^{2+})

Equations (1) and (2) represent environments either lacking in carbonate minerals or dominated by carbonate minerals, respectively. On the other hand, diffusion of soil or atmospheric CO_2 into water results in the following reaction (Clark and Fritz, 1997):

(3) $CO_{2\,(g)} + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$

The importance of each species is a function of pH, whereby H_2CO_3 dominates at pH levels below 6.4, HCO_3^- is prevalent at an intermediate pH range of 6.4 to 10.3, and CO_3^{2-} is the major species at higher pH values (Clark and Fritz, 1997).

Dissolved organic carbon (DOC) in non-polluted rivers is mostly a product of soil leaching, although it can also be derived from in-situ biological production and anthropogenic inputs (Meybeck, 1993; Hope et al., 1994). In the case of DOC, the carbon is sourced from the degradation of dead biomass by biotic processes (Clark and Fritz, 1997). Organic carbon is present initially in the form of primary vegetation components, such as lignin, cellulose and plant protein. As biodegradation proceeds further, these compounds are transformed into more recalcitrant substances such as humic and fulvic acids.

Rivers are an important conduit of organic and inorganic carbon transport between the land and ocean, providing a combined global carbon flux of around 0.7 Pg C yr^{-1} exported to the ocean. However, carbon is also lost from rivers via gas efflux and it is estimated that about 0.23 Pg C yr^{-1} is outgassed to the atmosphere as CO_2 (Cole et al., 2007). This CO_2 originates primarily from soil and mineral carbonate inputs, but can also be produced from the degradation of DOC within the river.

A recent study by Lapierre et al. (2013) suggested that the biological and photochemical degradation of DOC can provide significant contributions to dissolved riverine CO_2 and therefore, to aquatic CO_2 fluxes. This research suggested that the photochemical degradation potential of DOC increases with greater terrestrial inputs, resulting in increased export of CO_2 from the river waters.

The significance of each source of CO_2 is dependent on watershed ecology and geology. A study by Mayorga et al. (2005), using $^{13}C/^{12}C$ and ^{14}C techniques, suggested that the bulk of the CO_2 carbon efflux in the Amazon River is sourced from young organic matter. Research on the Mississippi River has found that either soil respiration or in-situ respiration of organic matter can dominate, depending on the section of river studied; the former being more important upstream and the latter predominating in the lower reaches (Butman and Raymond, 2011).

Anthropogenic influences can also strongly affect carbon cycling in rivers, with input of organic wastes significantly increasing the carbon content of affected rivers. Research by Jarvie et al. (1997) on UK rivers discharging into the Humber estuary, found considerable CO_2 overpressures in sections affected by industrial and municipal waste. Similarly, a study by Daniel et al. (2002) concluded that increased concentrations of DIC and DOC in the Piracaba River, Brazil, were due to sewage effluent discharge.

Additional human-induced effects on fluvial carbon cycling can include the artificial input of $CaCO_3$ via agricultural liming (Raymond et al., 2008), large contributions of soil carbonate to rivers due to agricultural soil erosion (Van Ooost et al., 2007) and the building of dams which increase decomposition of DOC, and enhanced CO_2 and CH_4 outgassing from the impounded reservoirs and river sections immediately downstream of dammed areas (Guérin et al., 2006).

1.3 Stable Carbon Isotope Studies of DOC and DIC

Studies of the stable carbon isotope composition of riverine DOC and DIC can help clarify carbon cycling processes within tropical rivers. Stable isotope values are measured in units of per mil (‰), relative to the Vienna Pee Dee Belemnite (V-PDB) standard, based on the following equation:

(4) $$\delta^{13}C = \left(\frac{R_{sample} - R_{std}}{R_{std}}\right)x10^3$$

In the above, “R_{sample}” and “R_{std}” represent the $^{13}C/^{12}C$ ratio in the sample of interest and the V-PDB standard, respectively. The isotopic composition of a particular carbon species can be used as an indicator of its origin and of subsequent processes leading to its modification (Clark and Fritz, 1997).

This makes stable isotope analysis a valuable tool in environments where carbon is derived from various sources. All carbon within rivers is ultimately sourced from atmospheric CO_2, organic carbon, or carbonate minerals (Meybeck, 1993; Hope et al., 1994), each with a characteristic range of $\delta^{13}C$ values (fig. 2). Atmospheric CO_2 has a $\delta^{13}C$ value of roughly -8‰, organic and respired carbon derived from C3 and C4 vegetation averages around -27‰ and -12.5‰ respectively, and marine carbonates are about 0‰ (Clark and Fritz, 1997; Hoefs, 2009; Ghosh and Brand, 2003).

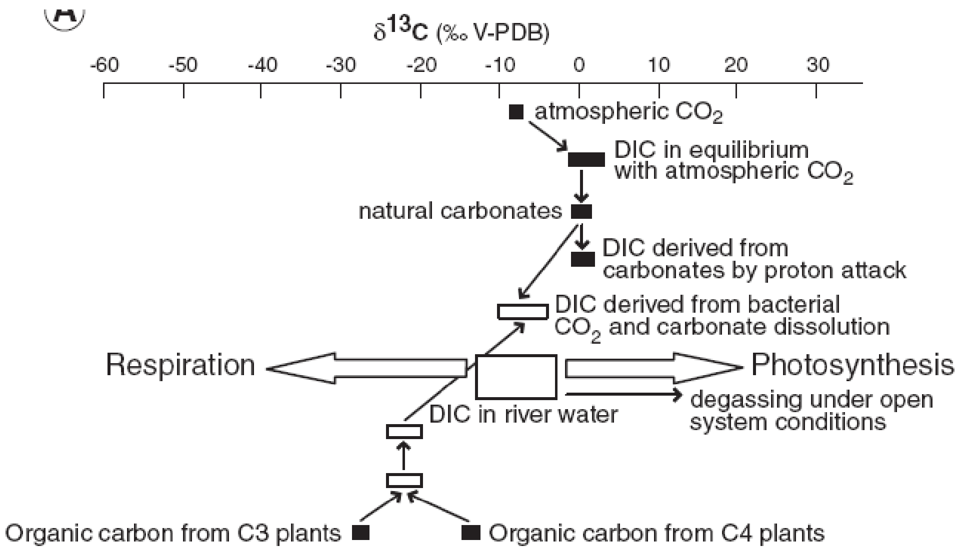


Figure 2: δ^{13}C values of carbon from different components (from Dubois et al., 2010)

The carbon isotope composition of a particular compound can also undergo modification subsequent to production. For example, soil CO_2 normally has an isotope composition identical with that of its source organic material, but undergoes diffusive fractionation as it moves through soil air spaces due to the differing diffusional velocities of the lighter versus heavier isotope. The end result is that the residual soil CO_2 undergoes a ^{13}C enrichment of around 4.4‰, due to the more rapid diffusion of ^{12}C through the soil pore air space (Cerling, 1991).

Biological processes can also influence the δ^{13}C values of various carbon species. Organisms utilizing carbon substrates as a source of energy show a preference for ^{12}C, due to its more rapid reaction rate owing to kinetic and thermodynamic considerations. Thus, as a carbon pool becomes progressively degraded by biological uptake, there is a tendency towards increasing ^{13}C-enrichment of the residual carbon (Mackenzie and Lerman, 2006).

By-products of biological activity also tend to be more ^{13}C-depleted relative to the parent material. This is observed with plant uptake of CO_2, in which plant tissues can be ^{13}C-depleted by more than 20 ‰, as well as with bacterial uptake of carbon substrates (Farquhar et al., 1989). In the case of methane production, the latter process can fractionate carbon as much as 90 ‰ relative to precursor materials (Whiticar et al., 1986).

Few papers have addressed the topic of stable isotopic analyses of carbon cycling in tropical rivers, with only a single short study involving fluvial $\delta^{13}C_{DIC}$ in Southeast Asia (Stephens and Rose, 2005). In research focusing on the Amazon River by Quay et al. (1992), ^{13}C-depletions in DOC, DIC and POC were observed from the headwaters towards the river's mouth (ranging from -26 ‰ to -32 ‰ for POC, -28 ‰ to -30 ‰ for DOC and -12 ‰ to -26 ‰ for DIC). The researchers concluded that these trends were a result of increasing inputs of ^{13}C-depleted POC from adjoining tributaries.

In another study by Brunet et al. (2009) concerning the Nyong River in Cameroon, a $\delta^{13}C_{DIC}$ range of -22.8 ‰ to -7.5 ‰ was observed. The authors concluded that this isotopic variation was due to fractionation via aquatic photosynthesis and CO_2 degassing, based on positive correlations of $\delta^{13}C_{DIC}$ with pH concomitant with negative correlations of pCO_2 and [DOC].

A somewhat diffuse explanation for $\delta^{13}C_{DIC}$ variations was proposed by Stephens and Rose (2005) for the Niah River watershed in Malaysian Borneo. The river waters displayed $\delta^{13}C_{DIC}$ values ranging from -14.5‰ to -4.8‰, with a progressive ^{13}C-enrichment from the headwaters towards the oceans. Stephens and Rose surmised that this was due to the mixing of organic matter-derived carbon with ^{13}C-enriched sources along the river's length (atmospheric CO_2, terrestrial limestone, marine waters and ^{13}C-enriched CO_2 resulting from in-situ photosynthesis).

For the Congo River Basin, Bouillon et al. (2012) found $\delta^{13}C_{DIC}$ values that were ^{13}C-enriched relative to C3 plant sources but depleted relative to atmospheric CO_2. They attributed it to mixed inputs from dissolution of carbonate minerals, seasonal photosynthetic activity and CO_2 outgassing.

This review shows that fluvial carbon cycling characteristics can differ significantly even in environments sharing similar climatic and ecological regimes. Any study of stable carbon isotope systematics in riverine systems therefore should include both inorganic and organic carbon, since the dynamics of these carbon types are often coupled.

1.4 Study Objectives

The purpose of this study was to use stable carbon isotopes to determine the origin and fate of carbon within the Langat and Kelantan watersheds, both located in the Malaysian Peninsula, and use this information to fill the paucity of information concerning the stable isotope systematic of carbon cycling in Southeast Asian watersheds. In doing so, this research provides the first reconnaissance study of riverine carbon cycling in this region, which will help further clarify the role of tropical rivers in the global carbon cycle.

2.0 Methods

2.1 Site Description

Field work was carried out within the Malaysian Peninsula, in two watersheds located on the east and west coasts: the Dengkil Sub-basin portion of the Langat River watershed in the western-central region of the peninsula and the Kelantan River Basin in the northeast (fig. 3). These basins were selected to determine the effects of river size, watershed urbanization, and differing monsoon regimes on local carbon cycling characteristics.

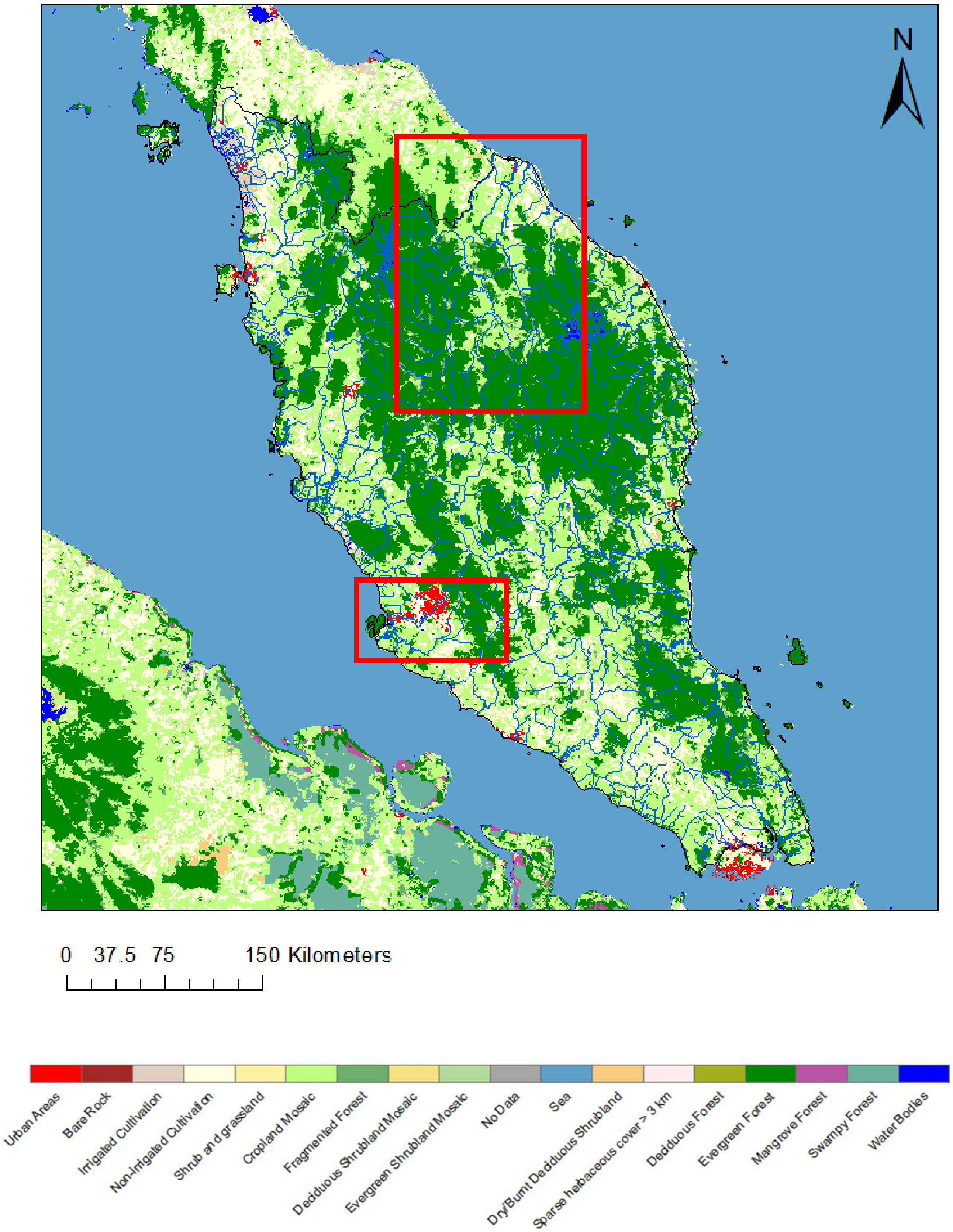


Figure 3: The locations of the Langat and Kelantan Basins within Peninsular Malaysia (enclosed in red boxes on the southwest and northeast coasts, respectively) and associated land cover types.

2.1.1 Regional Overview and Geography

Peninsular Malaysia is located between 1^{o}N and 7^{o}N latitude, and is bordered by Thailand to the north and Singapore to the south. The interior of the peninsula is dominated by mountainous terrain composed of granite and metasedimentary schists, of which the highest peak is Mount Tahan (2,191 m). These mountains extend across most of the peninsula in a north-south orientation (Hutchinson and Tan, 2009).

Rolling and undulating terrain exists between the individual mountain ranges and between the mountains and the coast. Within these landscapes, karst is present in many locations as isolated limestone hills that rise above the surrounding topography (Hutchison and Tan, 2009). Coastal areas are dominated by more recent alluvium, composed of unconsolidated sediments deposited by interior drainage systems (Chung, 1973).

About two-thirds of the peninsula is covered by rainforest and mangrove swamps, with the remainder composed of agricultural development and urban areas (Saw, 2007). Most of the remaining third (~42,000 km^{2}) of the land area of Peninsular Malaysia is dominated by oil palm plantations, with smaller areas devoted to rubber trees and various types of food crops (Koh and Wilcove, 2008).

The peninsula is subject to a tropical climate, experiencing average annual temperatures of around 30^{o}C and a cumulative annual rainfall of 2,500 mm (Saw, 2007). The strongest seasonal controls are provided by the Southwest Indian Monsoon (SWM) and the Northeast Asian Monsoon (NEM), which provide abundant precipitation from April to May, and May to November, respectively (Juahir et al., 2011; Koopmans, 1972) (fig. 4). Based on precipitation records collected from multiple sites on the Malaysian Peninsula and averaged over 29 years (1975 to 2004), the lowest mean seasonal rainfall of 466 mm occurs during June, July and August, while the highest mean seasonal rainfall of 769 mm occurs during September, October and November (Wong et al., 2010). The high seasonal average corresponds to the last three months of the NEM, while the low seasonal average is coincident with the Northern Hemisphere summer inter-monsoonal period.

This seasonal pattern of monsoonal precipitation is due to the position of the Malaysian Peninsula just north of the equator: the landmass is affected by the movement of the Intertropical Convergence Zone (ITCZ), a belt of intense convective activity that lies near the equator. During the Northern Hemisphere (NH) summer, increasing sea surface temperatures (SST) north of the equator and warming of the East Asian landmass results in the migration of the ICTZ northwards (fig. 4). This causes surface winds to flow from the Indian Ocean towards the northeast, causing the onset of the SWM and therefore, intense precipitation in the ITCZ and East Asia.

During the NH winter, increases in SST occur south of the equator and the East Asian landmass begins to cool. In response, the ITCZ migrates southwards of the equator and surface winds begin to flow towards the southwest, following the zone of convection. The zone of precipitation then moves south of the equator, with the resulting NEM characterized by rainfall as far south as Northern Australia.

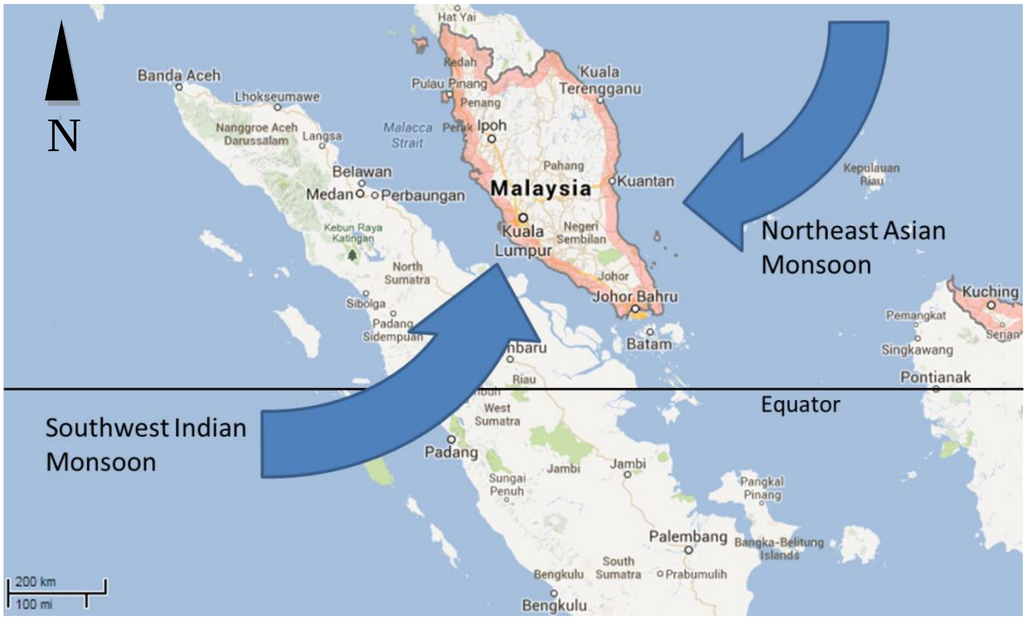


Figure 4: Surface wind direction during the Southwest Indian and Northeast Asian Monsoons.

2.1.2 The Dengkil Sub-basin

2.1.2.1 Physical Characteristics and Geology

The Dengkil Sub-basin covers an area of 1,240 km^2 and is a constituent of the Langat River Watershed, which covers 2,271 km^2 of land. The Langat River is located in one of the most urbanized watersheds in Malaysia, with close proximity to the capital city of Kuala Lumpur (population ~1.6 million). Much of the river is surrounded by urban development or cultivated land along its course, with more undisturbed forested areas present upstream (table 1, fig. 5).

While a thorough vegetative study of the Langat Basin has yet to be carried out, previous surveys in the watershed have shown that the natural forest vegetation is dominated by evergreen trees from the dipterocarp family (*Dipterocarpaceae*), which are plant types that utilize the C3-photosynthetic pathway. C4 plants are known to be present in lesser quantities, with a species of bamboo (*Gigantochloa scortechinii*) being the only confirmed representative of this group that is present in the sub-basin (NAHRIM, 2005).

With regards to cultivars, the most prominent plant types are oil palm (*Elaeis guineensis*) and rubber trees (Hevea brasiliensis), which comprise most of the cultivated land surfaces in the Langat Basin (NAHRIM, 2005). As with the naturally-occuring dipterocarp types, these plants are examples of C3 vegetation. Coconut (*Cocos nucifera*) and rice (*Oryza sativa*) plantations, also C3 types, are present in the watershed to a lesser extent.

Table 1: Land-use pattern of Dengkil sub-basin (Data from Yang et al., 2011)

Watershed Component	**Surface Area (km^2)**	**% Area**
Forest	398.66	32.16
Other	0.65	0.05
Oil Palm	13.18	1.06
Agriculture	466.37	37.62
Grassland	14.57	1.18
Bare land	22.18	1.79
Urban	307.22	24.78
Water	16.91	1.36
TOTAL	***1239.74***	***100***

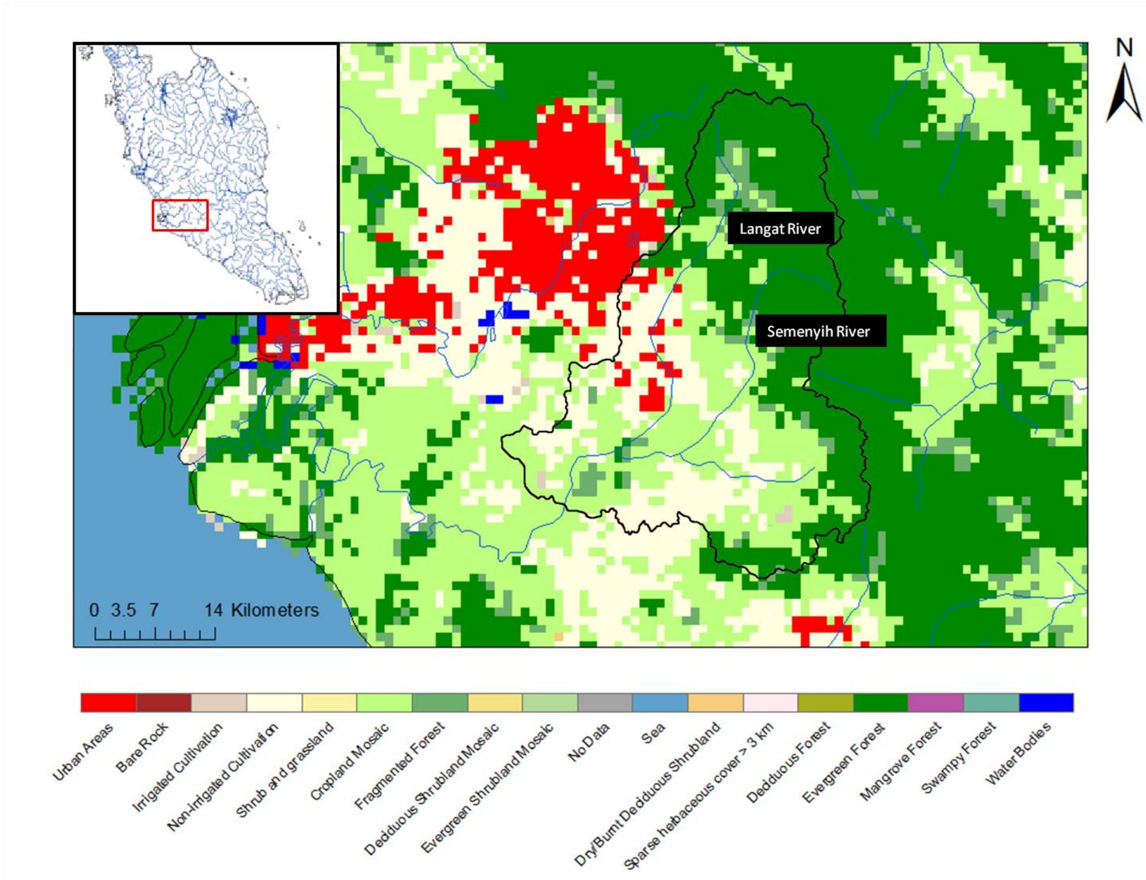


Figure 5: Detail of GIS land cover data of the Langat Basin, showing the Dengkil Sub-basin outlined in black (based on Yang et al., 2011).

Mountainous terrain dominates upstream Langat River in the northeastern portion of the sub-basin. Elevations can be as high as 1,000 m above mean sea level (msl), although most areas are below 500 m msl. Hilly areas prevail in the mid-portion of the basin, with elevations ranging from 50 m to 150 m msl. The final section of the sub-basin is composed of lowlands and floodplains averaging no more than 20 m msl (NAHRIM, 2005). The Langat river drains from the Langat Reservoir, which is an artificial water body with an full-water-supply area of 2.27 km^2 and a water-carrying capacity of 3.36 x 10^7 m^3 (NAHRIM, 2005).

Quaternary alluvium dominates the basin geology near the sub-basin outflow point at the town of Dengkil, while granitic bedrock is more significant upstream (Chung, 1973). The metasedimentary schists of the Hawthorn Formation (Middle to Upper Silurian, about 350 million years old) comprise most of the bedrock of the sub-basin, with extensive outcropping in the upstream portion of the basin (fig. 6). These rocks are overlain by a soil layer 5 to 10 m thick, comprised of clayey silt and silty clay (NAHRIM, 2005). Limestone outcrops and karst terrain appear to be absent within the sub-basin itself, although exposure of these rock types occur in adjacent areas to the north. (Chung, 1973).

In the downstream portion of the Dengkil Sub-basin, there is extensive outcropping by the Kenny Hill/Kajang Formation. This unit is composed of meta-sandstone, quartz, phyllite and shale. The soil cover over the Kenny Hill/Kajang formation varies between 1 m and 5 m in thickness, and may contain laterite and a hard iron pan. In areas where intruding quartz veins are present, the soil layer is observed to contain small angular quartz fragments within a clayey sand matrix (NAHRIM, 2005).

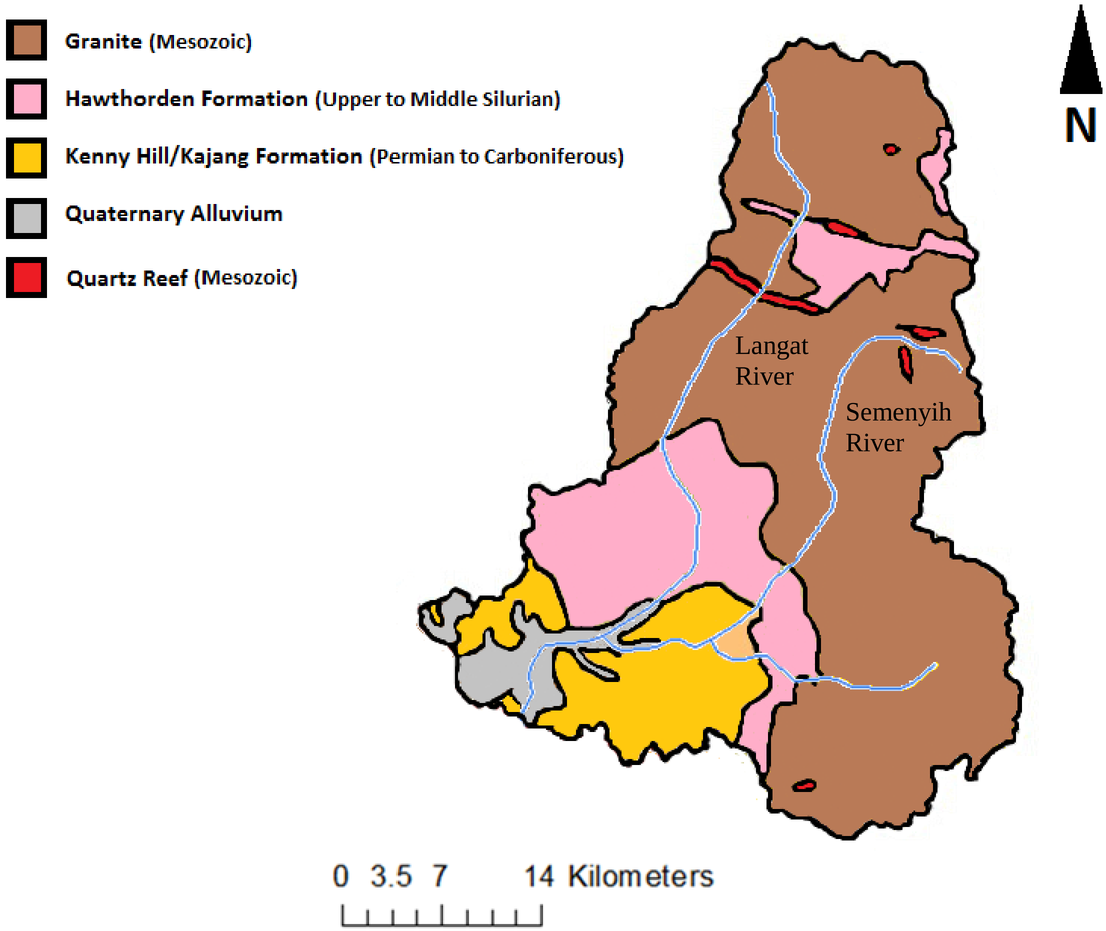


Figure 6: A geological summary of the Dengkil Sub-basin. Modified from NAHRIM (2005).

Due to heavy urbanization of the watershed, Langat River has been classified as having a water quality index (WQI) of 58.1 to 75, corresponding to polluted and moderately polluted waters, respectively. The three largest sources of point-source pollution (defined as pollutants derived from a singular, identifiable source), based on estimated rates of discharge into the Langat River, are industrial factory wastes, sewage treatment plant effluents and sand mine waste (Juahir et al., 2011).

Much of this pollution is concentrated in the downstream region of the Dengkil Sub-basin (Azrina et al., 2006). This area has been classified as "class IV" according to the five tier water quality classification scheme used by NAHRIM, which signifies that the river waters are severely polluted and fit only for irrigation purposes. In contrast, the upstream section of the sub-basin was found to be of a higher water quality category: class II or "good" water quality.

Similarly, Juahir et al. (2011) classified the upstream and downstream halves of the Dengkil Sub-basin as subject to low and medium point source pollution, respectively, based on statistical analyses of multiple water quality parameters (fig. 7).

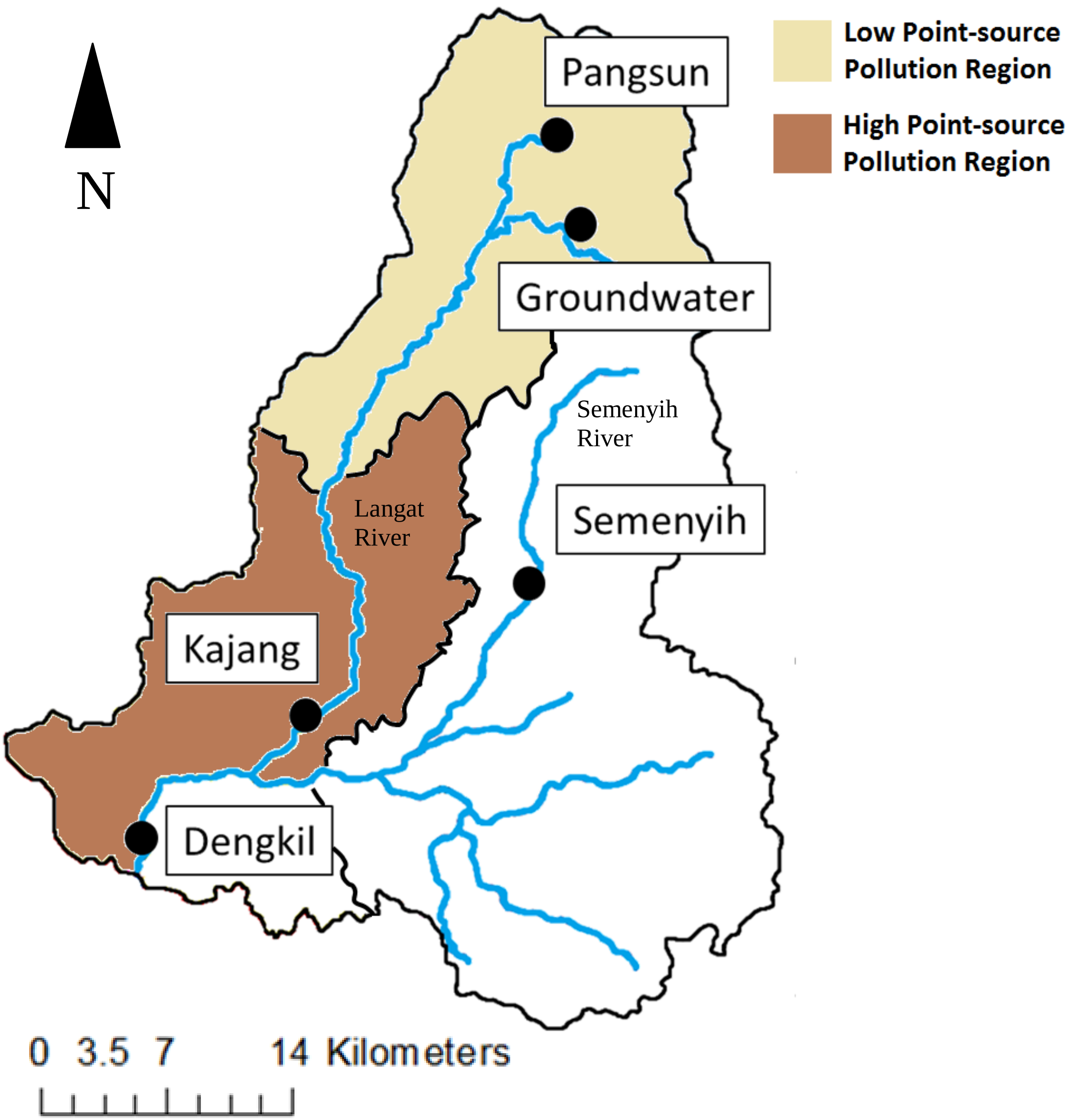


Figure 7: Regions of high and low point-source pollution in the Dengkil Sub-basin with respect to the sampling locations. Areas in white are un-measured. Modified from Juahir et al. (2011).

2.1.2.2 Climate and Hydrology

A tropical, humid climate characterizes the Langat Basin, which experiences an average annual temperature of 28.6^{o}C, and averaged cumulative precipitation of 2400 mm per year (Noorazuan, 2003; Lassen et al., 2004). Both the SWM and NEM affect the region, bringing precipitation during the summer and winter months, respectively. Temperature remains relatively constant throughout the year, varying no more than 1.2^{o}C.

The Langat River is about 141 km in length, of which 80 km is within the Dengkil Sub-basin where it varies from 10 m to 31 m in width (Suki et al., 1988). Based on measurements made at the Dengkil village outflow point, the average total flow volume of the Langat River in the sub-basin over 44 years of data collection (1965-2009) was calculated to be 8.57 x 10^8 m^3 by Yang et al. (2011). The authors estimated that 4.29 x 10^8 m^3 of this value was comprised of baseflow, with the remainder contributed by surface runoff and precipitation inputs.

Using ^{18}O/D river water measurements, and the archived river flow and precipitation data for the years of 2010 and 2011 (see section 2.5), evaporation and evapotranspiration rates were estimated by project co-leader M.I. Syakir (personal communication) to be 236 ± 15 x 10^3 g H_2O m^{-2} yr^{-1} and 1442 ± 131 x 10^3 g H_2O m^{-2} yr^{-1}, respectively.

2.1.3 The Kelantan River Basin

2.1.3.1 Physical Characteristics and Geology

The Kelantan River basin is located on the northeast coast of the Malaysian Peninsula and encompasses an area of 12,391 km^2 (Koopmans, 1972). As compared to the Langat Basin, there is less urbanization along the Kelantan River, with the city of Kota Bharu (population ~580,000) at the mouth of the river being the largest urban centre in the watershed. Estimates of land-use patterns in the Kelantan State, which shares much of the same boundaries as the watershed, show the largest areas being covered by forest and cropland (68 % and 26 %, respectively) (NAHRIM, 1998; table 2, fig. 8).

The lowland and hill rainforests in the Kelantan Basin are comprised of Dipterocarp trees, with oak-laurel forests present in the tropical highlands and montane ericaceous forest at higher altitudes (NAHRIM 1998). Agriculture in the basin as a whole consists mostly of oil palm and rubber trees, although tobacco (*Nicotiana tabacum*) and rice plantations are more dominant closer to the river mouth (Ahmad et al., 2009). The remainder of the land cover is a mixture of mangrove swamps, urban development, shrub land, water bodies and mining areas (NAHRIM, 1998; table 2).

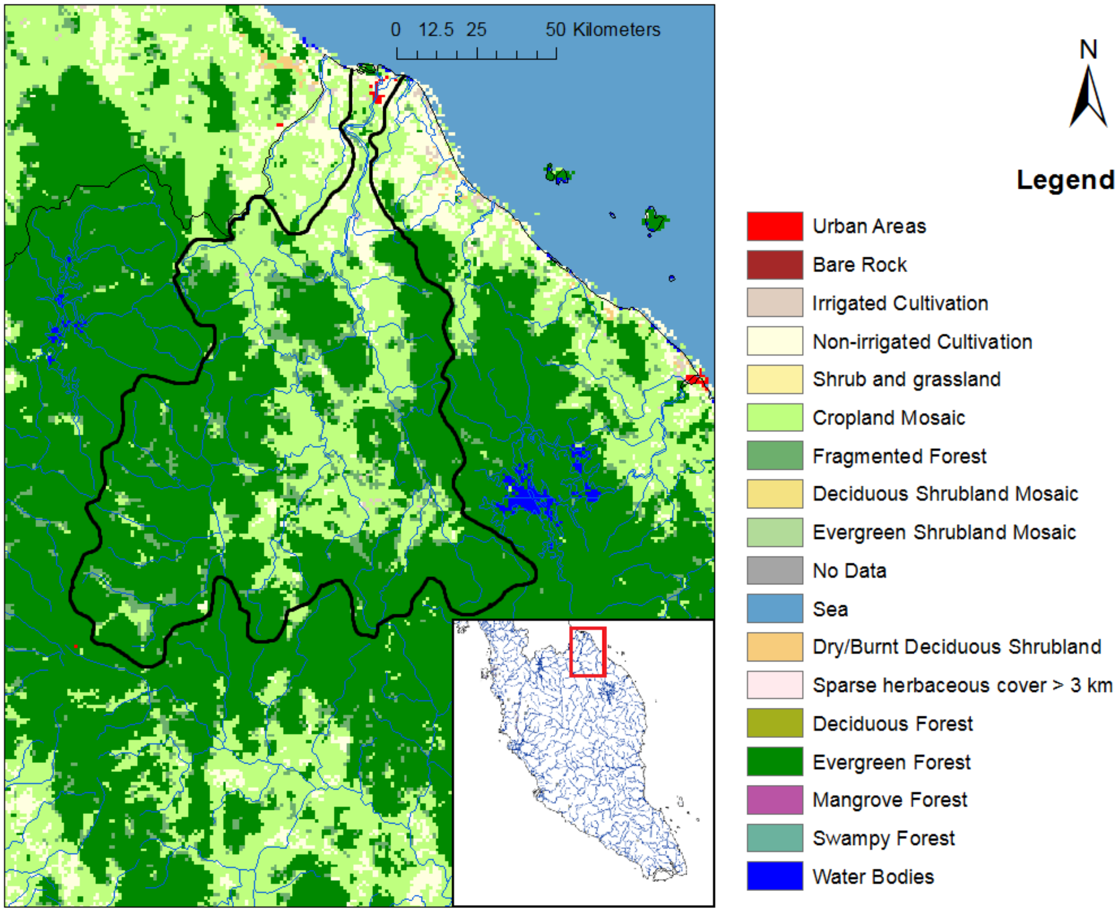


Figure 8: Detail of GIS land cover data of the Kelantan Basin (outlined in black, based on NAHRIM 1998).

Table 2: Land-use pattern of Kelantan State (data from NAHRIM, 1998).

Watershed Component	Surface Area (km^2)	% Area
Forest	1,012,608	67.97
Mangrove Swamp	21,170	1.42
Agriculture	392,368	26.34
Mining Areas	174	0.01
Shrubland	56,334	3.78
Other	7,090	0.48
TOTAL	***1,489,744***	***100***

Given the lesser extent of urbanization and agricultural land-use in the Kelantan Basin, as compared to Langat, water quality is generally good throughout the basin: the main stem of the Kelantan River has been assessed as ``class 2`` along its entire length. Where pollution sources exist, these consist of industrial effluent from palm oil mills and rubber factories, and discharge from sewage and landfill sites (NAHRIM, 1998).

The downstream portion of the river is dominated by Quaternary alluvium, with granitic and calcareous bedrock being more important upstream in the southern portion of the basin (Chung, 1973). These rocks include the granites of the Main Range (Triassic) and the Kelantan Schist (Paleozoic), with marine limestones and shales of the Gua Musang Formation (Upper Paleozoic) present in lesser quantities (Zakaria, 1975; fig. 9).

The mountainous terrain of the eastern and western portions of the watershed is overlain by a granitic soil cover of coarse sand and clay. This layer averages about a metre in depth, but can be up to 18 m deep in localized areas. In the extreme east and west of the southern portion of the basin, the soil is a fine sandy loam that rarely exceeds more than a few metres in depth. A variable soil cover reaching up to 9 m in depth covers the remaining one-third of the basin (Ibbitt et al., 2002).

The Kelantan River originates within steep and rugged terrain, with elevations ranging between 1,000 m to 2,000 m msl (NAHRIM, 1999). As it approaches the coast in the northern end of the watershed, the river meanders through a deltaic plain 117 km^2 in area, prior to discharge into the ocean.

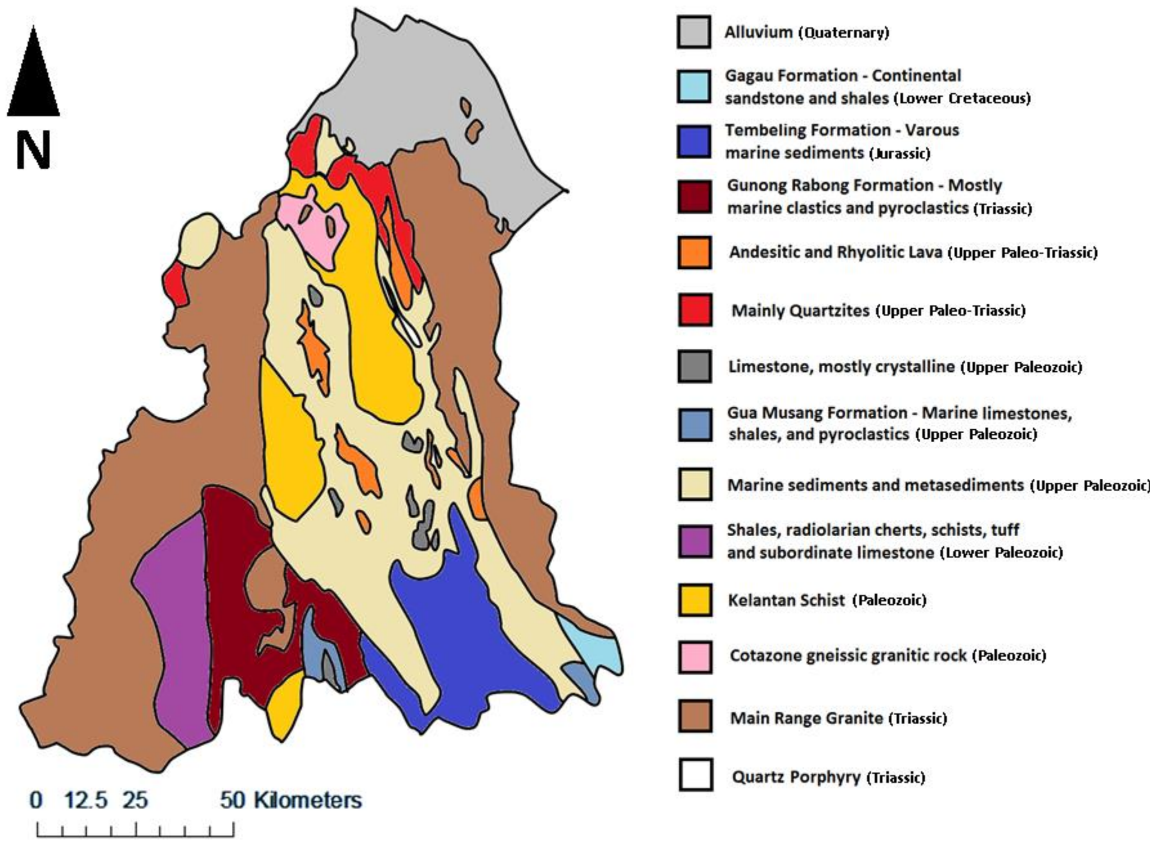


Figure 9: A geological summary of the Kelantan Basin. Modified from Zakaria (1975).

2.1.3.2 Climate and Hydrology

Mean annual temperatures are similar to that of the Langat Basin, around $27^{o}C$, with an average annual rainfall of 3,119 mm (Zakaria, 1975). The NEM provides the bulk of the local precipitation, occurring between the months of November and May, although rainfall may occur throughout the year in lesser quantities (Koopmans, 1972).

The main stem of the Kelantan River is 248 km long with a mean annual runoff of 557.5 m^3 s^{-1}, based on a 40-year set of flow-rate measurements (1950-1990) taken at the

Gullemard Bridge just upstream of the village ofTanah Merah (Ibbitt et al., 2002). Calculations of evaporation and evapotranspiration rates by M.I. Syakir derived from river water $^{18}O/D$ data (personal communication; see section 2.1.2.2) yielded no discernible evaporation, but an evapotranspiration rate of 1,303 ± 71 g H_2O m^{-2} yr^{-1} was obtained.

2.2 Sampling and Collection

Each site in the Langat and Kelantan basins was sampled bimonthly over the course of 20 months, from May 2010 to December 2011. River water samples were initially sampled using a glass 250 mL Pyrex media bottle for the first 3 months of sampling. The bottle was tied to a length of string and lowered over the side of a bridge into the river to 1 m depth. From August 2010 onwards, a 1 L acrylic Lamotte water sampler was used for sites and sampling times where water level exceeded 1 m, which was also lowered from bridges for sample retrieval in most locations. The exception was the Kota Bharu site in the Kelantan Basin near the river mouth, where a boat was used to gather samples from mid-river.

The Dengkil sub-basin of the Langat Watershed was selected to avoid the influence of sea water input, which may be significant in its downstream estuarine section. Within the sub-basin, samples were collected from 5 localities (fig. 10). Three sites were located on the Langat River and selected within project limitations to provide an adequate profile along the river's length. One location was upstream near the source (Pangsun), another close to the mid-stream point (Kajang) and the last was downstream at the sub-basin outflow point (Dengkil). Samples from an adjoining tributary, the Semenyih River, were also obtained in order to clarify influences from adjoining streams on carbon cycling and water chemistry in the main Langat River stem.

A groundwater site near the upstream location of Pangsun was sampled during the same dates as the river sampling. The samples were retrieved from a faucet installed into the ground, adjacent to a goat farm that utilized the groundwater for agricultural use. The approximate depth of the water table is 20 feet, and the regional aquifer is a hard-rock type residing in silicate bedrock of low primary porosity and overlain by soil (Manap, 2011).

Initial sampling was performed by the author and project co-leader (M.I. Syakir) for the first 3 months in both watersheds. The remainder was carried out by two trained local assistants, Ana Salwa in the Dengkil Sub-basin and Zamri Has in the Kelantan Basin, whom also organized the measurement of water chemistry parameters (see below), temperature, sample maintenance and shipping to the University of Ottawa.

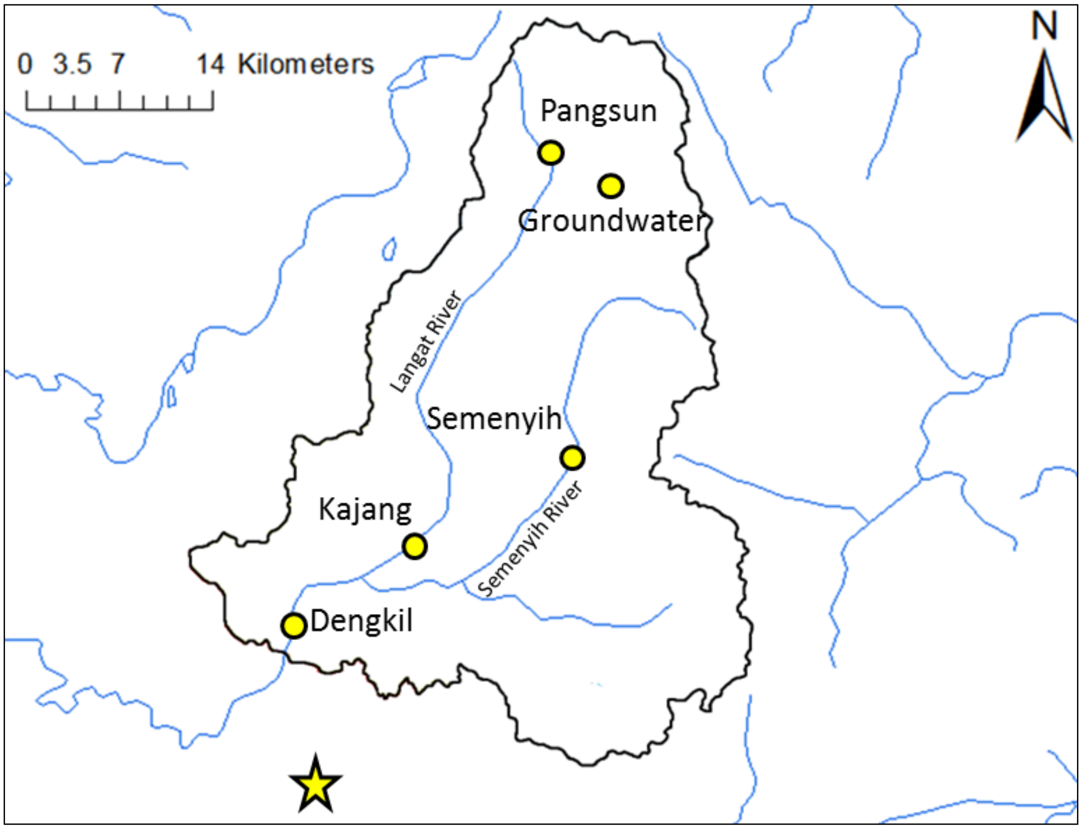


Figure 10: The location of sampling sites in the Dengkil sub-basin. Sampling sites are indicated by yellow circles, while the NOAA precipitation data collection site is shown by the yellow star (see also section 2.5).

In the Kelantan watershed, 3 sample points were selected: two on the Kelantan River (Tanah Merah and Pasir Mas) and one closer to the river's mouth (Kota Bharu). Groundwater was sampled from a location just southeast of Kota Bharu, in a small village called Bukit Marak (fig. 11). The samples were taken from a faucet installed in the ground and adjacent to a home, which was fed by an alluvial aquifer about 20 feet in depth.

Note that all river and groundwater sampling stations are within the downstream portion of the watershed. As with the Dengkil sub-basin, groundwater and river water was sampled during the same dates and sampling time frame.

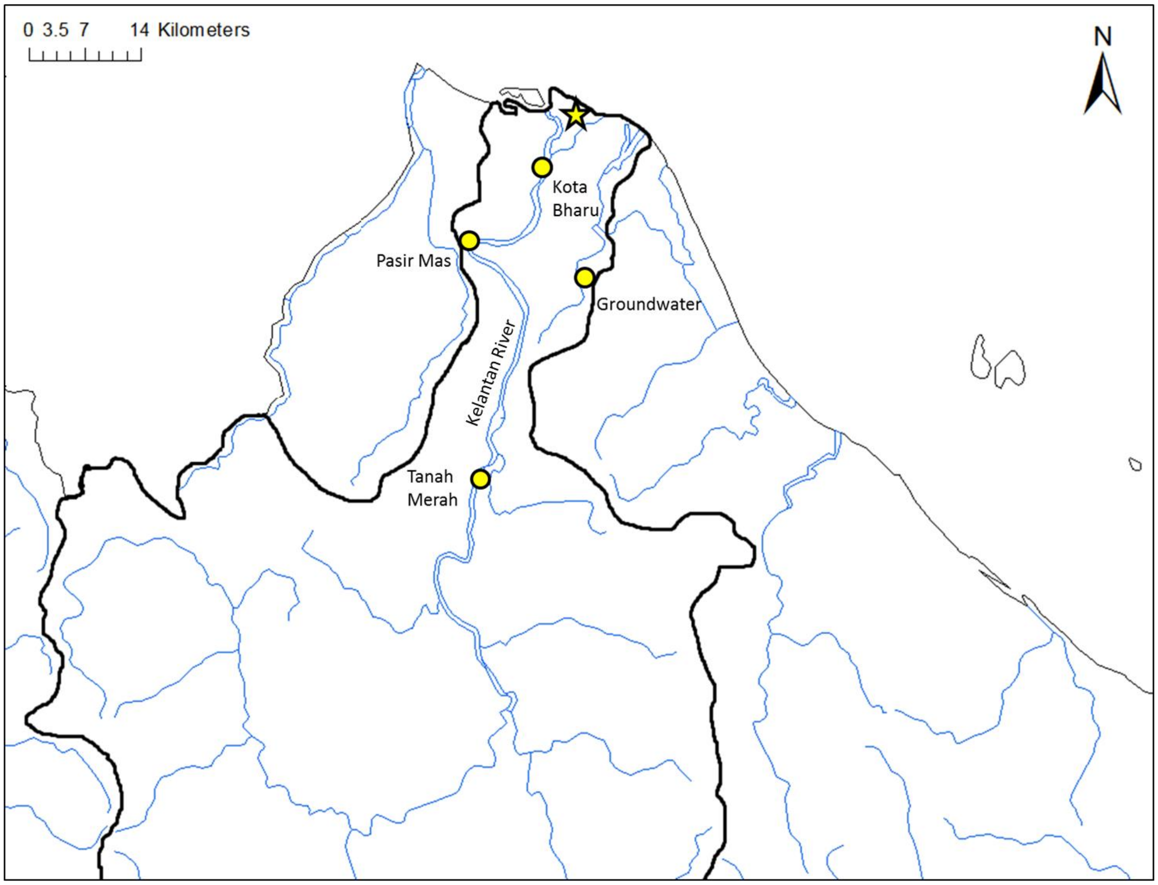


Figure 11: The location of water sampling sites within the Kelantan Basin, indicated by yellow circles, and the NOAA precipitation monitoring station indicated by a yellow star (see section 2.5).

Upon retrieval, the water was filtered via syringe through 0.45 μm membrane filters of 25 mm diameter and placed in 40 ml amber glass bottles. To inhibit biological activity, 1 ml of 8.0×10^{-4} M $HgCl_2$ was added to each bottle prior to analysis. In addition to 0.125 inch rubber septa, a Teflon-backed Flexiseal disc was added to the amber-glass bottles to ensure sample integrity. Upon collection, the bottles were stored in a refrigerator at 4^oC prior to analysis.

Total dissolved solids (TDS), electroconductivity (EC), pH and water temperature were measured on site in the Dengkil sub-basin, using a Hannah Instruments HI 98129

Combo Tester instrument. Precisions for the above measurements are ± 2 % for TDS and EC, ± 0.05 for pH and ± 0.5°C for water temperature. The instrument was calibrated for pH measurements using buffer solutions of pH 10 and 7 immediately prior to field work, and for TDS with a 1,500 ppm calibration solution.

While the above measurements were collected in the Dengkil Sub-basin during most of the sampling period, instrument malfunction prevented the collection of data for the Kelantan Basin. In substitution, pH data collected by the Malaysian Department of the Enviroment (DOE) during 2010 and 2011 from Tanah Merah and Kota Bharu were used. As these measurements were not contemporaneous with our sampling periods, annually-averaged pH values for 2010 and 2011 were calculated from the available DOE data. All these measurements are listed in appendices 1 and 2, and a summary of the number of analyses performed is shown below in table 3.

Table 3: Summary of the number of analyses performed in the Kelantan and Dengkil watersheds.

Parameters	"n" Samples - Dengkil Sub-basin					"n" Samples - Kelantan Basin				***TOTALS***
	Pangsun	Kajang	Dengkil	Semenyih	Groundwater	Tanah Merah	Pasir Mas	Kota Bharu	Groundwater	
[DIC]	40	40	40	40	39	35	35	30	35	334
[DOC]	40	40	40	40	39	35	35	30	35	334
$\delta^{13}C_{DIC}$	40	40	40	40	39	35	35	30	35	334
$\delta^{13}C_{DOC}$	40	40	40	40	39	35	35	30	35	334
pH	35	35	35	34	35	N/A	N/A	N/A	N/A	174
EC	35	35	35	35	35	N/A	N/A	N/A	N/A	175
TDS	35	35	35	35	35	N/A	N/A	N/A	N/A	175
Ca	38	38	40	38	39	34	33	20	31	311
Fe	38	38	40	38	39	23	23	20	31	290
K	38	38	40	38	39	20	20	20	31	284
Mg	38	38	40	38	39	34	23	20	31	301
Mn	38	38	40	38	39	23	23	20	31	290
Na	38	38	40	38	39	23	23	20	31	290
Cl	40	38	40	38	40	34	34	28	34	326
Si	29	29	30	29	29	19	18	17	18	218
SO_4	40	38	40	38	40	34	34	28	34	326
Zn	38	38	40	38	39	31	30	26	29	309
Sr	38	20	30	29	29	33	33	20	33	265
NO_3	13	29	30	29	40	25	25	21	26	238

2.3 Laboratory Analyses

Samples were shipped from Malaysia to the University of Ottawa every two months. The DIC/DOC concentrations and $\delta^{13}C$ were measured on a MAT Finnigan Delta Plus IRMS at the University of Ottawa's G.G. Hatch Stable Isotope Laboratory, following the method of St-Jean (2003). Instrument analytical precisions (2σ) are ± 2% and ± 0.2 ‰ for concentration and stable isotope measurements, respectively. Between three sample replicates, reproducibility was better than ± 25 % for concentration measurements and ± 1 ‰ for $\delta^{13}C$. Isotope values are measured relative to VPDB and expressed in delta-notation, based on equation 4. The summary of $\delta^{13}C$ measurements can be found in appendices 3 and 4.

Cation and anion analyses were performed on filtered samples stored in 30 ml Nalgene bottles. These were run using a Varian Vista-Pro inductively coupled plasma – atomic emission spectrometer (ICP-AES) and a Dionex DX-100 ion chromatograph, respectively. Samples were measured in 5 ml volumes, with those destined for cation analyses acidified to 1% with HNO_3 beforehand. For the ICP-AES, precisions and accuracies were better than 5% and 15% respectively. The DX-100 had instrument precisions and accuracies better than 17% and 1% at the 0.1 ppm level. The relevant data can be found in appendices 3 and 4. With all data, outlier values were identified and omitted via calculation of the interquartile range (IQR) of each dataset (see Upton and Cook (1996) for more detail on methods).

2.4 DIC Concentration and Stable Isotope Determinations

DIC can be separated into its constituent parts based on reaction (3) and using the below relationships (Clark and Fritz, 1997):

(5) $$K_{CO_2} = \frac{[H_2CO_3]}{P_{CO_2}}$$

(6) $$K_1 = \frac{[H^+][HCO_3^-]}{[H_2CO_3]}$$

(7) $$K_2 = \frac{[H^+][CO_3^{2-}]}{[HCO_3^-]}$$

Via rearrangement and substitution, and recalling that the total DIC is the sum of H_2CO_3, HCO_3^- and CO_3^{2-}, the above equations can be used to calculate P_{CO2}:

(8) $$P_{CO_2} = \frac{[DIC]}{\left(\frac{K_1}{[H^+]} + \frac{K_1K_2}{[H^+]^2} + 1\right) * K_{CO_2}}$$

Using the results obtained through equation (8), where *[DIC]* is a measured value and $[H^+]$ is calculated from the pH data, riverine CO_2 fluxes to the atmosphere were then estimated using the following equation:

(9) $$F = k\left[(C_{water} - C_{equilibrium}) \bullet \frac{m_{CO2}}{RT}\right]$$

where F is the evasion flux in g C m^{-2} day^{-1}, C_{water} is the partial pressure of CO_2 within the river in atm, $C_{equilibrium}$ is the partial pressure in atm of dissolved CO_2 in equilibrium with the atmosphere, k is the gas transfer velocity in m d^{-1}, R is the ideal gas constant in units of m^3 atm K^{-1} mol^{-1}, mCO_2 is the molecular mass of CO_2 and T is air temperature in K. The value of $C_{equilibrium}$ was taken to be 390 ppm, based on the averaged mean global atmospheric CO_2 values for 2010 and 2011 that were measured by NOAA (data retrieved from the NOAA database: ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_annmean_gl.txt).

As k measurements were not available for Langat River, the values of 1.92 m d^{-1} and 4.0 m d^{-1} was chosen from Mook et al. (1970) and Richey et al. (1990), respectively. The former value is indicative of stagnant rather than running river waters, and the latter is in the upper range for large, tropical rivers (Dubois et al., 2010). Therefore, these selected values provide a lower and upper-end estimate of gas efflux. For T, an average basin temperature of 303.15 K (30^{o}C) was assumed.

2.5 Ancillary Data

Information on daily river flow rates, air temperature, water level, and water quality parameters (BOD, TSS, COD and DO) were obtained from the Department of Environment (DOE), Ministry of Natural Resources and Environment of Malaysia, for both the Langat and Kelantan Basins (appendices 5 and 6). Daily precipitation amounts in the Langat and Kelantan Basins were obtained from the online NOAA database, and were measured at the Kuala Lumpur International airport on the southwest edge of the

Dengkil sub-basin, and at Kota Bharu near the mouth of the Kelantan River (see figs. 10 and 11, and appendix 1).

3.0 Results

3.1 Langat Basin Data

3.1.1 $\delta^{13}C_{DOC}$ and [DOC]

DOC concentrations in groundwater and the upstream surface water site of Pangsun show similar averages (± 1 standard deviation) of 155 ± 135 μM C and 193 ± 78 μM, respectively. The downstream sites of Kajang and Dengkil, as well as the Semenyih tributary, show higher concentrations of 329 ± 159 μM, 348 ± 201 μM and 307 ± 133 μM, respectively (table 4). There is no indication of any seasonal patterns, although the presence of an interannual trend may be suggested by somewhat higher [DOC] during 2010 as compared to 2011 (fig. 12, top). The [DOC] at all locations show large variations throughout the sampling period, with large peaks occurring in late August 2010 and early to mid-July 2011 at all sites.

The $\delta^{13}C_{DOC}$ values (fig. 12, bottom) on average show more ^{13}C-depleted values in the upstream site and in groundwater (-29.5 ± 2.3 ‰ and -29.2 ± 2.9 ‰, respectively) than in the two downstream locations (-26.8 ± 2.4 ‰ and -26.1 ± 2.9 ‰ in Kajang and Dengkil, respectively). In general, the $\delta^{13}C_{DOC}$ signatures mostly fall within the -27.8 ±

2.9 ‰ band. Temporal patterns are unclear, although $\delta^{13}C_{DOC}$ is anomalously low in early July 2011 across all sites (fig. 12).

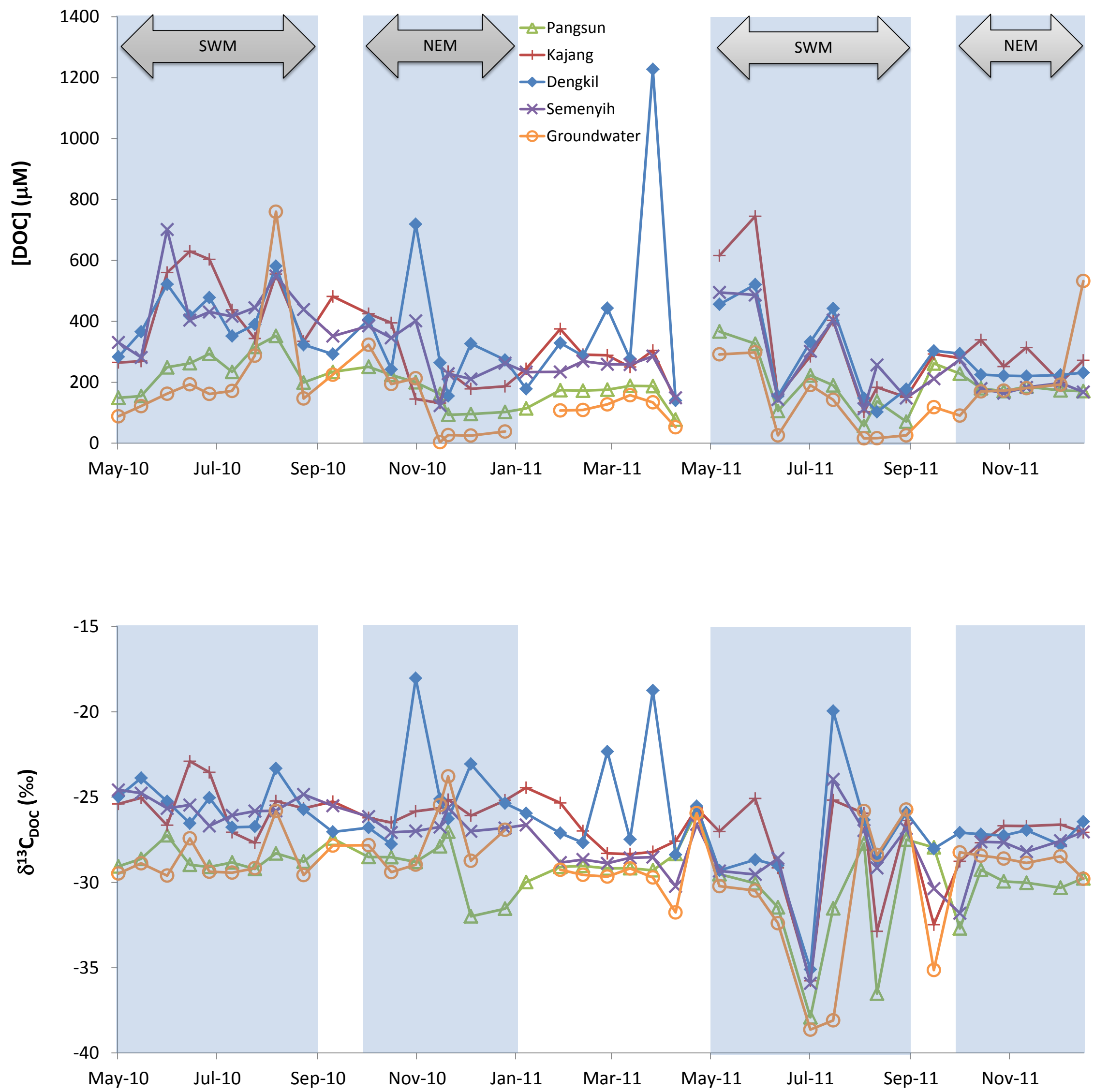


Figure 12: Temporal [DOC] and $\delta^{13}C_{DOC}$ trends in the Dengkil sub-basin. See appendix 3 for data.

Table 4: Summarized [DOC] and $\delta^{13}C_{DOC}$ data collected in the Dengkil Sub-basin. Data in appendix 3.

Site	Maximum $\delta^{13}C_{DOC}$ (‰)	Minimum $\delta^{13}C_{DOC}$ (‰)	Average $\delta^{13}C_{DOC}$ (‰)	Maximum [DOC] (μM)	Minimum [DOC] (μM)	Average [DOC] (μM)
Pangsun	-25.8	-37.9	-29.5 ± 2.3	367	57	193 ± 78
Kajang	-22.9	-35.8	-26.8 ± 2.5	745	103	329 ± 159
Dengkil	-18.0	-35.1	-26.1 ± 3.0	1228	103	348 ± 201
Semenyih	-24.0	-35.9	-27.5 ± 2.3	702	113	307 ± 133
Groundwater	-23.8	-38.6	-29.2 ± 3.0	760	3.3	155 ± 135

3.1.2 $\delta^{13}C_{DIC}$ and [DIC]

Groundwater samples show an average [DIC] value of 357 ± 204 μM, which is similar to averages at Pangsun (254 ± 199 μM) and in the Semenyih tributary (326 ± 107 μM). In contrast, the mid- to downstream samples at Kajang and Dengkil show more elevated concentrations (663 ± 430 μM and 520 ± 281 μM, respectively) (table 5). Temporal variations in [DIC] are distinct, with the highest increases appearing in August to December, during the NEM period in both 2010 and 2011 (fig. 13, top). The largest riverine [DIC] peaks during these periods are displayed by the mid-stream Kajang and down-stream Dengkil sampling sites.

The $\delta^{13}C_{DIC}$ data obtained from the Langat River and its tributaries (fig. 13, bottom) show comparable ranges across all river sites, with an average value of -13.1 ± 2.2 ‰. A more ^{13}C-depleted range of -20 ± 3.4 ‰ is present within groundwater. This relative ^{13}C-depletion, compared to the river sites, is consistent during most periods of sampling, with exceptions in October and early December of 2010, and late August in

2011. There are no clear trends in $\delta^{13}C_{DIC}$, with large ^{13}C-enriched values appearing periodically throughout the sampling period (fig. 13, bottom).

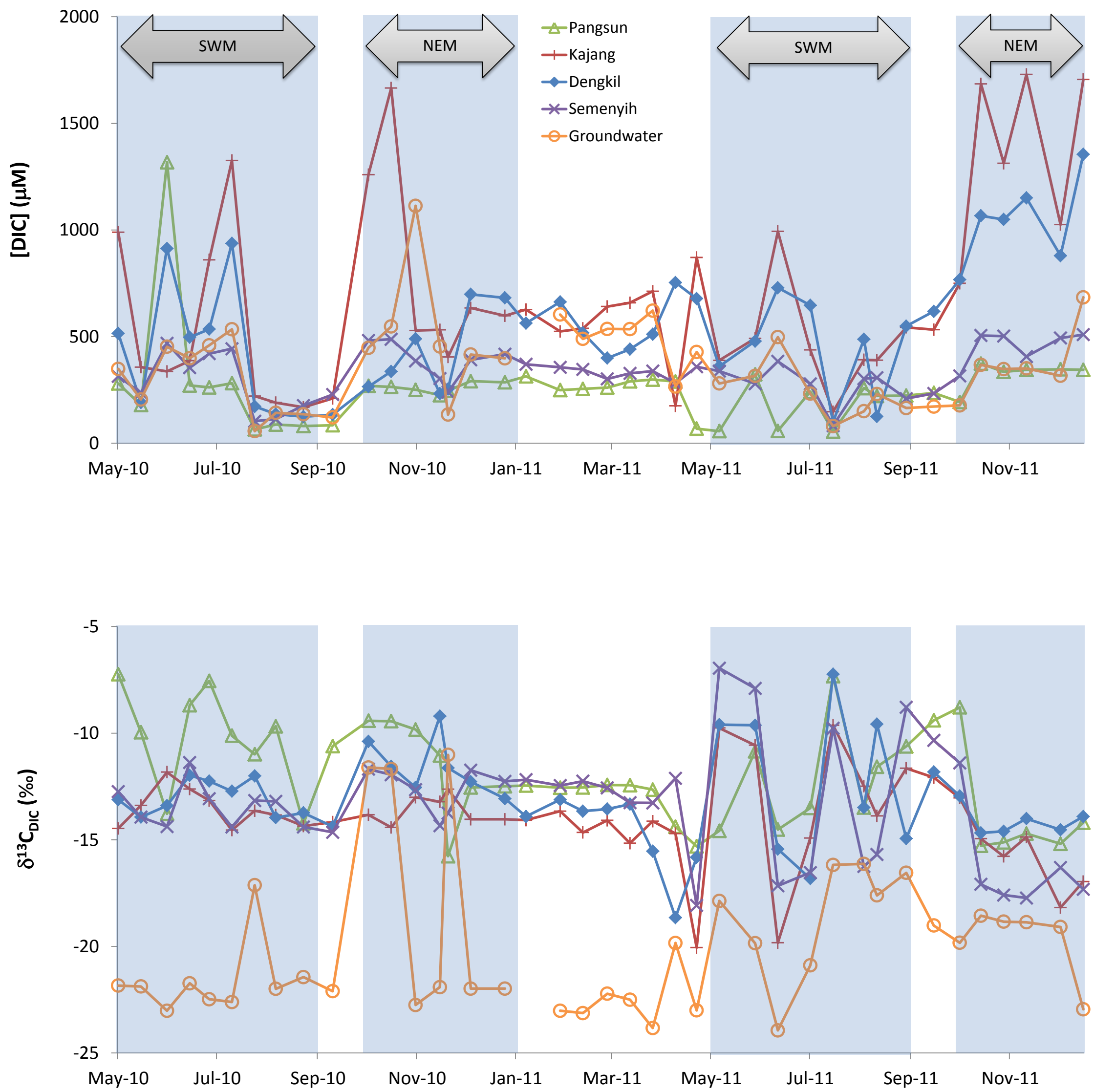


Figure 13: Temporal [DIC] and $\delta^{13}C_{DIC}$ trends in the Dengkil sub-basin. See appendix 3 for data.

Table 5: Summarized [DIC] and $\delta^{13}C_{DIC}$ data collected in the Dengkil Sub-basin. Data in appendix 3.

Site	Maximum $\delta^{13}C_{DIC}$ (‰)	Minimum $\delta^{13}C_{DIC}$ (‰)	Average $\delta^{13}C_{DIC}$ (‰)	Maximum [DIC] (μM)	Minimum [DIC] (μM)	Minimum [DIC] (μM)
Pangsun	-7.2	-15.8	-12.1 ± 2.4	1317	55	254 ± 199
Kajang	-9.6	-20.1	-14.0 ± 2.2	1729	148	663 ± 430
Dengkil	-7.2	-18.7	-13.1 ± 2.2	1355	99	520 ± 281
Semenyih	-7.0	-18.1	-13.4 ± 2.7	509	83	326 ± 107
Groundwater	-11.0	-23.9	-20.0 ± 3.4	1113	57	357 ± 204

3.1.3 Riverine pCO_2

Values of pCO_2 from all locations were calculated using equation (8). The results show that during most of the sampling period, river waters are supersaturated with CO_2 relative to atmospheric values (table 6, fig. 14). The riverine $epCO_2$ (excess pCO_2; ratio of river pCO_2 concentrations to atmospheric values) range from 0.6 to 54.6 (see appendix 7 for data). The highest partial pressures are observed in Kajang, and the lowest in Pangsun. Data from groundwater show even larger pCO_2 values, displaying an $epCO_2$ approaching 80 during some sampling periods.

Table 6: Summarized pCO_2 calculated from the Dengkil Sub-basin DIC data. Data in appendix 7

Site	Maximum pCO_2 (ppmv)	Minimum pCO_2 (ppmv)	Average pCO_2 (ppmv)	Average $epCO_2$
Pangsun	5310	240	2249 ± 1635	5.8
Kajang	21276	518	5743 ± 5377	14.7
Dengkil	12550	412	4658 ± 3619	11.9
Semenyih	10191	263	3008 ± 2212	7.7
Groundwater	30840	751	5920 ± 5672	15.2

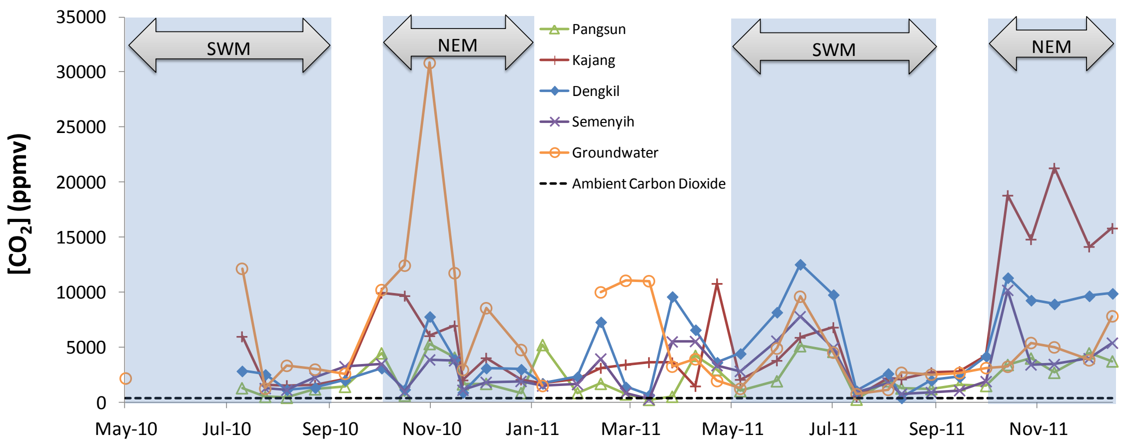


Figure 14: Temporal trends of [pCO_2] in the Dengkil sub-basin.

Temporal variation appears strong during the sampling periods, with generally lower pCO_2 at all sites roughly during July to October (SWM) of both years of collection, and higher levels during October to December (NEM). In between these periods, trends appear to be absent.

3.1.4 River Chemistry Data

Within all sites, the element present in the highest concentrations is chloride. In contrast, magnesium is the least significant constituent of the sample waters, and is found in the lowest concentrations (table 7, fig. 15). With the exception of magnesium and silicon, which are present in similar quantities in all locations, the other constituents are present in larger quantities within the mid- and downstream sites as compared to groundwater and upstream, the latter two sharing comparable cation and anion concentrations.

Table 7: Yearly averaged DIC/DOC and selected water quality data in the Dengkil sub-basin, ± 1 standard deviation. Data in appendix 3.

Constituent [mM]	*Groundwater*	*Pangsun*	*Kajang*	*Dengkil*	*Semenyih*
[DIC]	364.3 ± 205.9	226.17 ± 97.1	698.3 ± 453.2	550.0 ± 308.2	334.8 ± 110.8
[DOC]	165.7 ± 144.6	192.6 ± 76.0	324.5 ± 156.8	341.8 ± 197.3	300.7 ± 132.0
[Ca^{+}]	35.0 ± 40.3	57.7 ± 31.6	255.2 ± 118.6	212.3 ± 94.8	115.7 ± 39.6
[Fe^{3+}]	0.2 ± 0.4	3.6 ± 8.9	0.9 ± 1.5	0.8 ± 0.8	1.2 ± 1.3
[Mg^{2+}]	8.5 ± 2.9	28.6 ± 8.8	29.2 ± 12.6	31.5 ± 12.4	23.2 ± 7.4
[Mn^{2+}]	0.3 ± 0.2	0.1 ± 0.4	1.1 ± 2.2	0.2 ± 0.3	0.2 ± 0.4
[Na^{+}]	67.8 ± 28.5	89.1 ± 35.5	283.4 ± 155.7	270.6 ± 140.4	222.1 ± 381.2
[K^{+}]	56.8 ± 64.7	79.2 ± 103.2	215.3 ± 185.8	182.5 ± 232.8	200.3 ± 224.1
[Si^{4+}]	111.8 ± 77.3	171.4 ± 62.4	114.2 ± 86.4	102.5 ± 73.2	154.9 ± 58.1
[Sr^{2+}]	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1
[Zn^{2+}]	1.4 ± 1.9	1.0 ± 2.4	1.0 ± 2.0	0.5 ± 0.8	0.5 ± 0.7
[Cl^{-}]	126.2 ± 245.2	108.3 ± 246.6	400.7 ± 293.3	330.0 ± 264.0	308.8 ± 253.9
[NO_3^{-}]	6.0 ± 7.3	23.2 ± 19.0	76.8 ± 64.5	94.6 ± 58.9	45.5 ± 22.9
[SO_4^{2-}]	12.5 ± 7.8	15.6 ± 19.6	115.3 ± 36.7	105.1 ± 25.6	76.7 ± 28.4

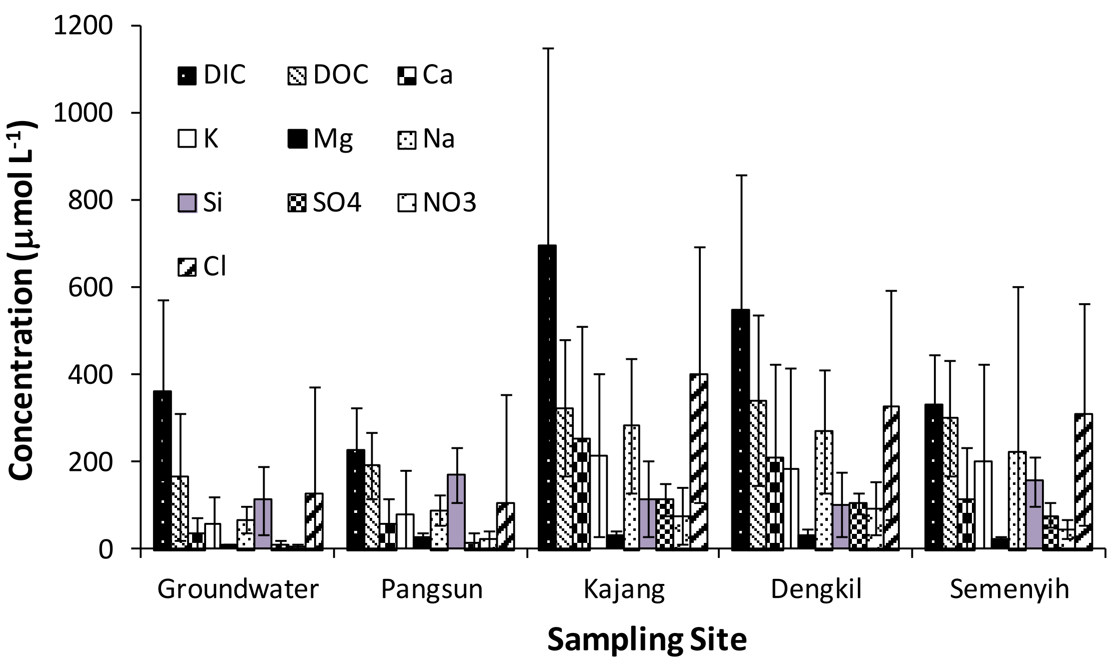


Figure 15: Averaged DIC/DOC and selected anion/cation concentrations for sampling locations within the Dengkil sub-basin (data in appendix 3). Error bars represent ± 1 standard deviation.

Some of the chemical constituents show clear temporal trends (figs. 16, 17 and 18). Calcium, magnesium and sodium show almost identical patterns of generally higher concentrations from May to September 2010 and April to December 2011, with lower concentrations present during the period of October 2010 to April 2011. Similarities exist also for potassium and chloride, which show maxima in late October 2010, late June 2011 and early October 2011 in the downstream sites and the Semenyih tributary. Trends in the other chemical species are unclear, although sulphate and nitrate are similar to calcium, magnesium and sodium in showing higher values during November to December 2011.

To investigate the accuracy and completeness of the chemical dataset, a charge balance was calculated. The sum of the positive and negative charges of all cations and anions were incorporated into the following equation:

(10) $$CBE = \frac{\sum cations - |\sum anions|}{\sum cations + |\sum anions|} \times 100$$

The resulting calculation of the CBE revealed averaged values in excess of 5 % in all sites: 47 % in Pangsun, 24 % in Kajang, 18% in Dengkil, 25 % in Semenyih and 56 % in groundwater. This may be due to analytical or sampling error, or uncertainties in the calculated HCO_3^- values. The latter were indirectly measured from [DIC] data measured in the laboratory and pH measurements that were collected prior in the field.

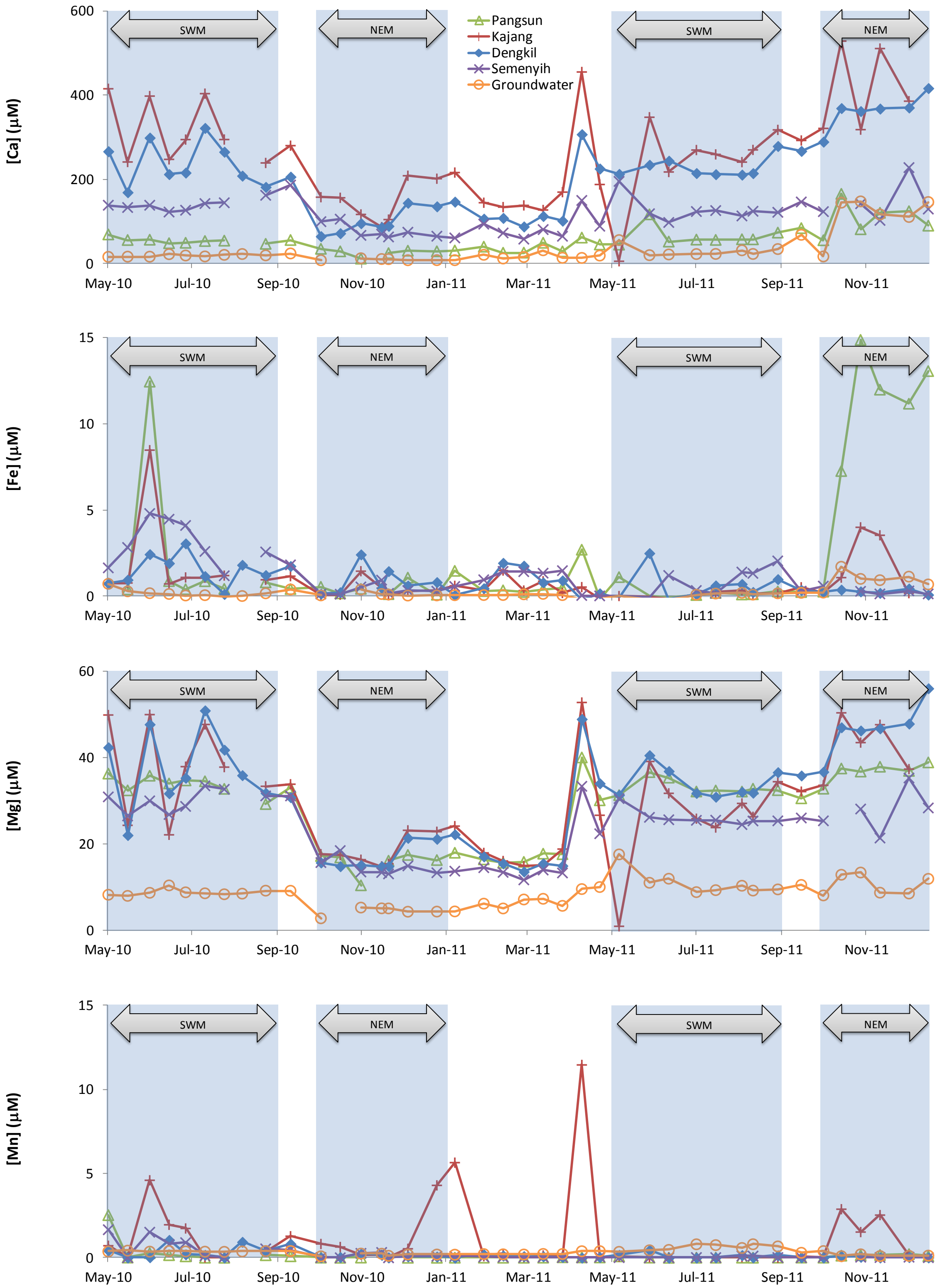


Figure 16: Temporal plots for Ca, Fe, Mg, and Mn in the Dengkil sub-basin. Data in appendix 3.

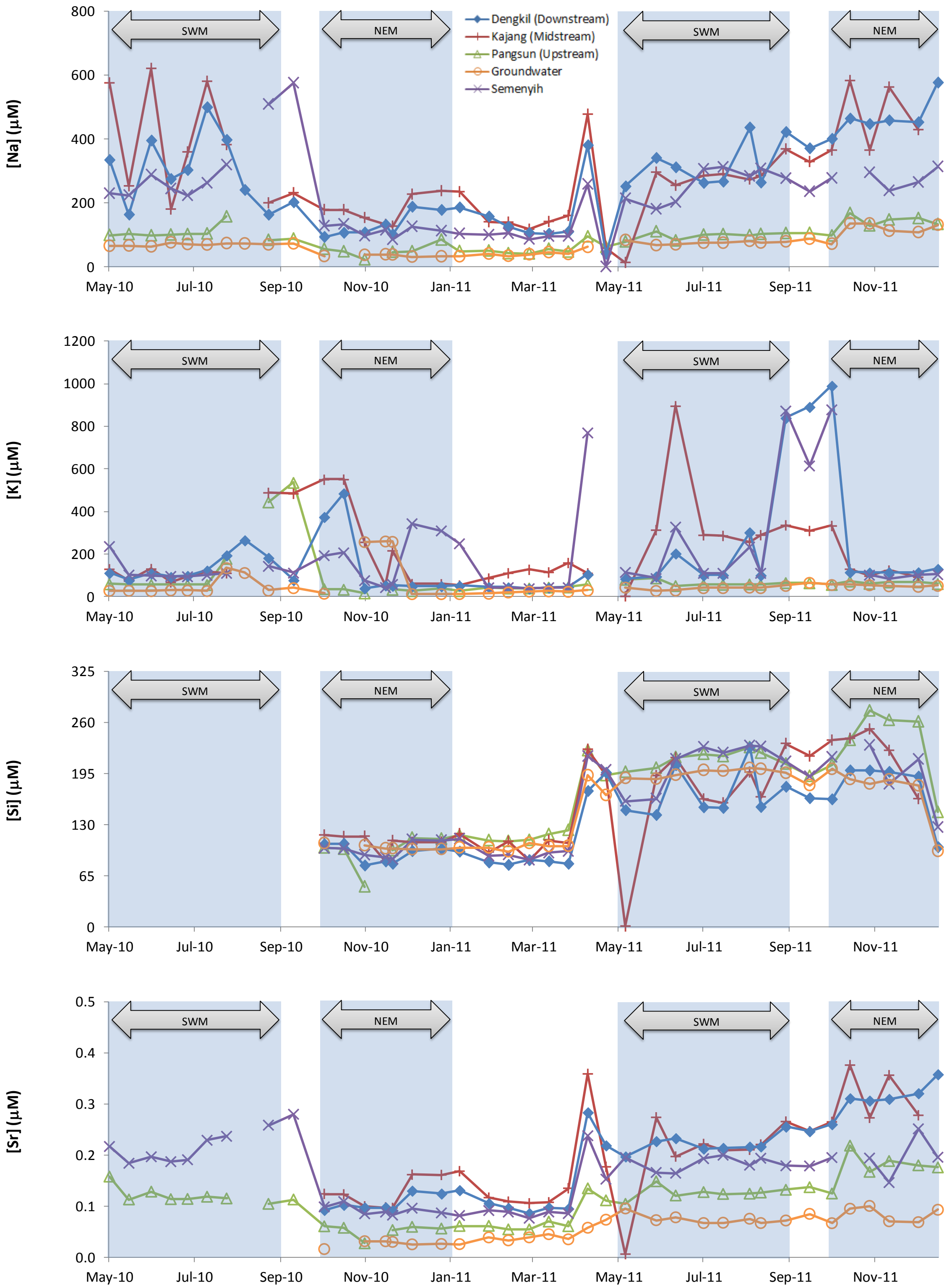


Figure 17: Temporal plots for Na, K, Si and Sr in the Dengkil sub-basin. Data in appendix 3.

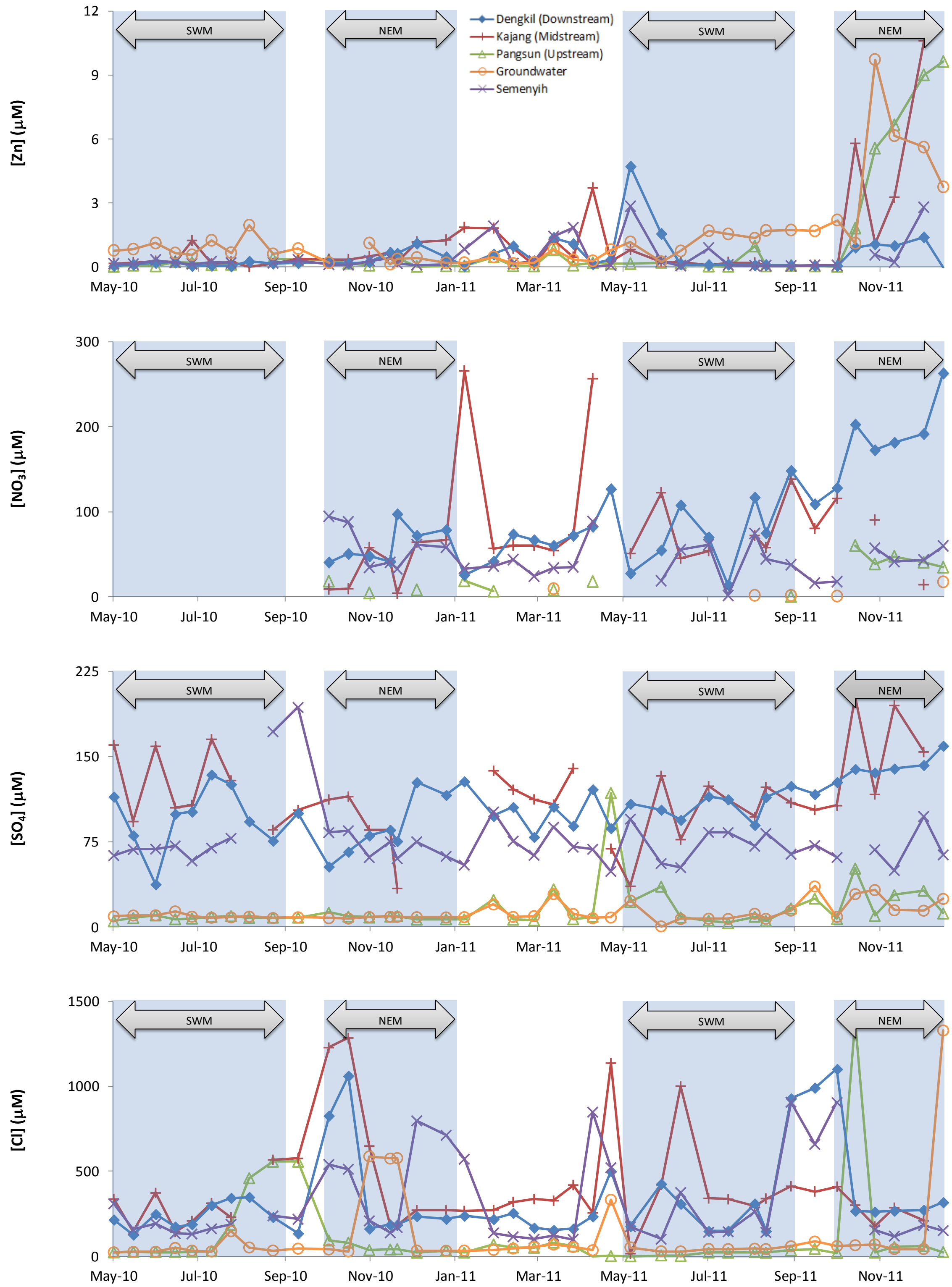


Figure 18: Temporal plots for Zn, NO_3, SO_4 and Cl in the Dengkil sub-basin. Data in appendix 3.

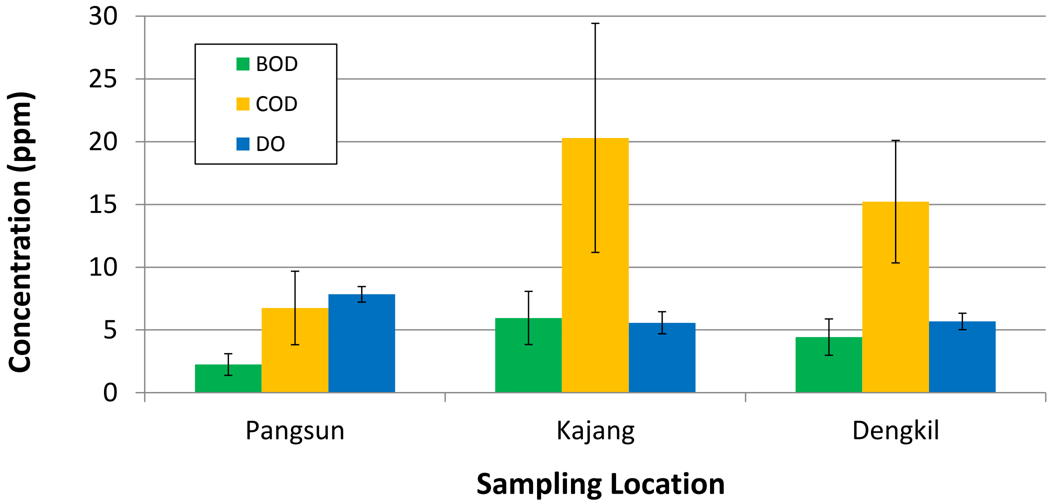


Figure 19: Averaged BOD, COD and DO values for sampling locations within the Dengkil sub-basin. Data in appendix 5. Error bars represent ± 1 standard deviation.

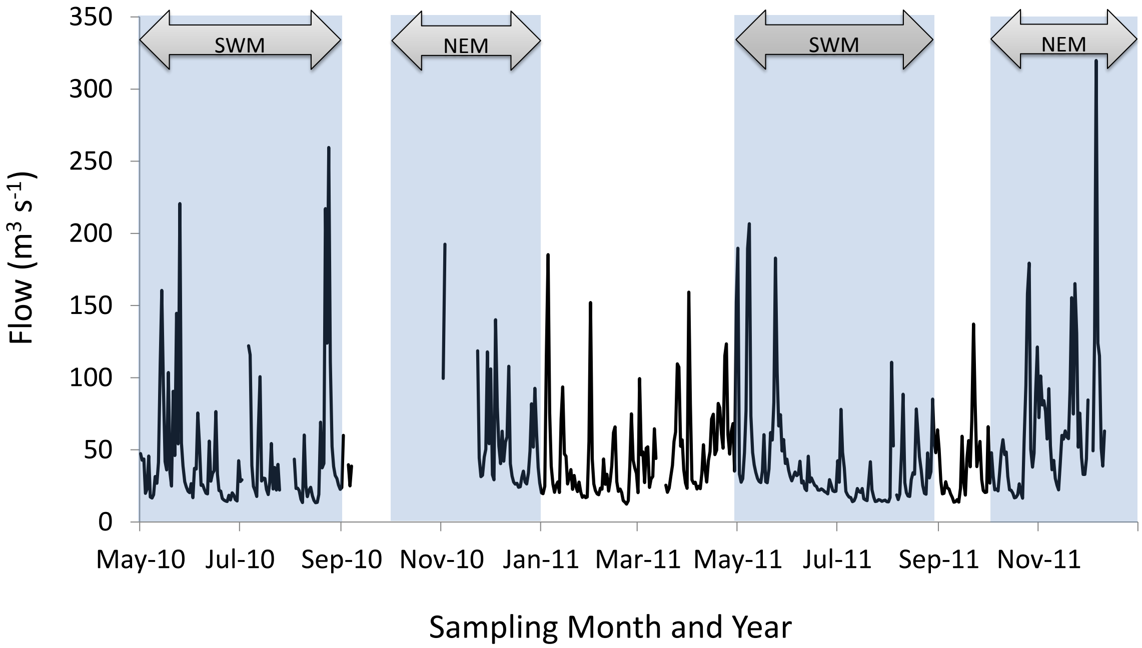
The water BOD data consistently show higher values in Kajang and Dengkil (5.96 ± 2.12 ppm and 4.43 ± 1.44 ppm, respectively), relative to the upstream site of Pangsun (2.25 ± 0.87 ppm). There are similar features in the COD data, which also show the downstream sites (20.30 ± 9.13 ppm and 15.22 ± 4.88 ppm, respectively) having more elevated values as compared to the headwaters (6.75 ± 2.93 ppm). In contrast, dissolved oxygen is higher in Pangsun (7.84 ± 0.62 ppm) as compared to Kajang (5.57 ± 0.88 ppm) or Dengkil (5.68 ± 0.66 ppm) (fig. 19).

3.1.5 Hydrology

The precipitation and river flow data show some degree of coincidence with the monsoonal periods, with the largest values observed during the NEM interval (fig. 20; data in appendix 13): daily precipitation reached a maximum of 91.5 mm during December 21, 2010, while flow reached a maximum rate of 319.9 $m^3 s^{-1}$ on December 6, 2011. In contrast, the lowest flow rate of 12.4 $m^3 s^{-1}$ was observed during the inter-monsoonal period on February 22, 2011.

In the Langat Basin, nevertheless, the correlation between river flow and precipitation for the date range of May 1, 2010 to December 31, 2011 is minimal ($R^2 < 0.001$). Perhaps the upstream damming of the Langat River and the associated regulation obscures any relationships that may exist. There is also no clear distinction between the two monsoon seasons with respect to river flow or precipitation, which may be due in part to the brevity of the study period and the insufficient temporal resolution of the data.

a)



b)

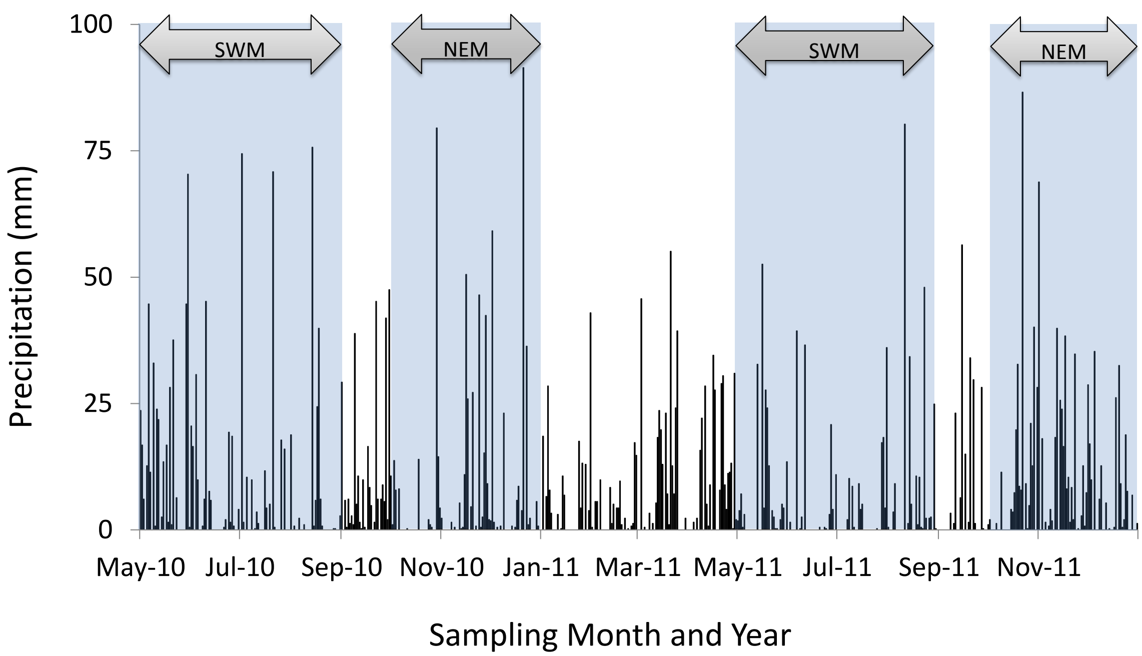


Figure 20: Plots of (a) river flow and (b) precipitation data measured at Dengkil station and Kuala Lumpur International Airport, respectively. Flow data was obtained from NAHRIM and precipitation amounts from the online NOAA database (see appendix 1 for data, and fig. 10 for sampling locations).

3.2 Kelantan Basin Data

3.2.1 $\delta^{13}C_{DOC}$ and [DOC]

Within the Kelantan Basin, the groundwater samples showed an average [DOC] value of 312 ± 158 μM (table 8). The riverine sites show similar [DOC] averages of 375 ± 160 μM, 394 ± 157 μM and 378 ± 169 μM at Tanah Merah, Pasir Mas, and Kota Bharu, respectively. While the groundwater displayed a lower averaged [DOC] than the river samples, this discrepancy was not consistent throughout the entire sampling period. Temporal trends are not uniform across all sites, but [DOC] appears to have been generally reduced during the period of early January 2011 to late March 2011 (fig. 21).

$\delta^{13}C_{DOC}$ values were similar across all locations, with averages of -27.2 ± 2.4 ‰, -26.2 ± 1.7 ‰, -26.6 ± 2.4 ‰ and -26.6 ± 1.9 ‰ in groundwater, Tanah Merah, Pasir Mas and Kota Bharu, respectively. With the exception of an anomalous groundwater ^{13}C-enrichment in early September 2011, $\delta^{13}C_{DOC}$ values fall within overall range of -30.2 ‰ to -21.0 ‰ during the sampling period at all sites (fig. 21; table 8).

Table 8: Summarized [DOC] and $\delta^{13}C_{DOC}$ data collected in the Kelantan Basin. Data in appendix 4

Site	Maximum $\delta^{13}C_{DOC}$ (‰)	Minimum $\delta^{13}C_{DOC}$ (‰)	Average $\delta^{13}C_{DOC}$ (‰)	Maximum [DOC] (µM)	Minimum [DOC] (µM)	Average [DOC] (µM)
Tanah Merah	-22.6	-29.3	-26.2 ± 1.7	725	194	375 ± 160
Pasir Mas	-21.0	-29.5	-26.6 ± 2.4	706	181	394 ± 157
Kota Bharu	-22.1	-29.4	-26.6 ± 1.9	804	191	378 ± 169
Groundwater	-15.8	-30.2	-27.2 ± 2.4	784	140	312 ± 158

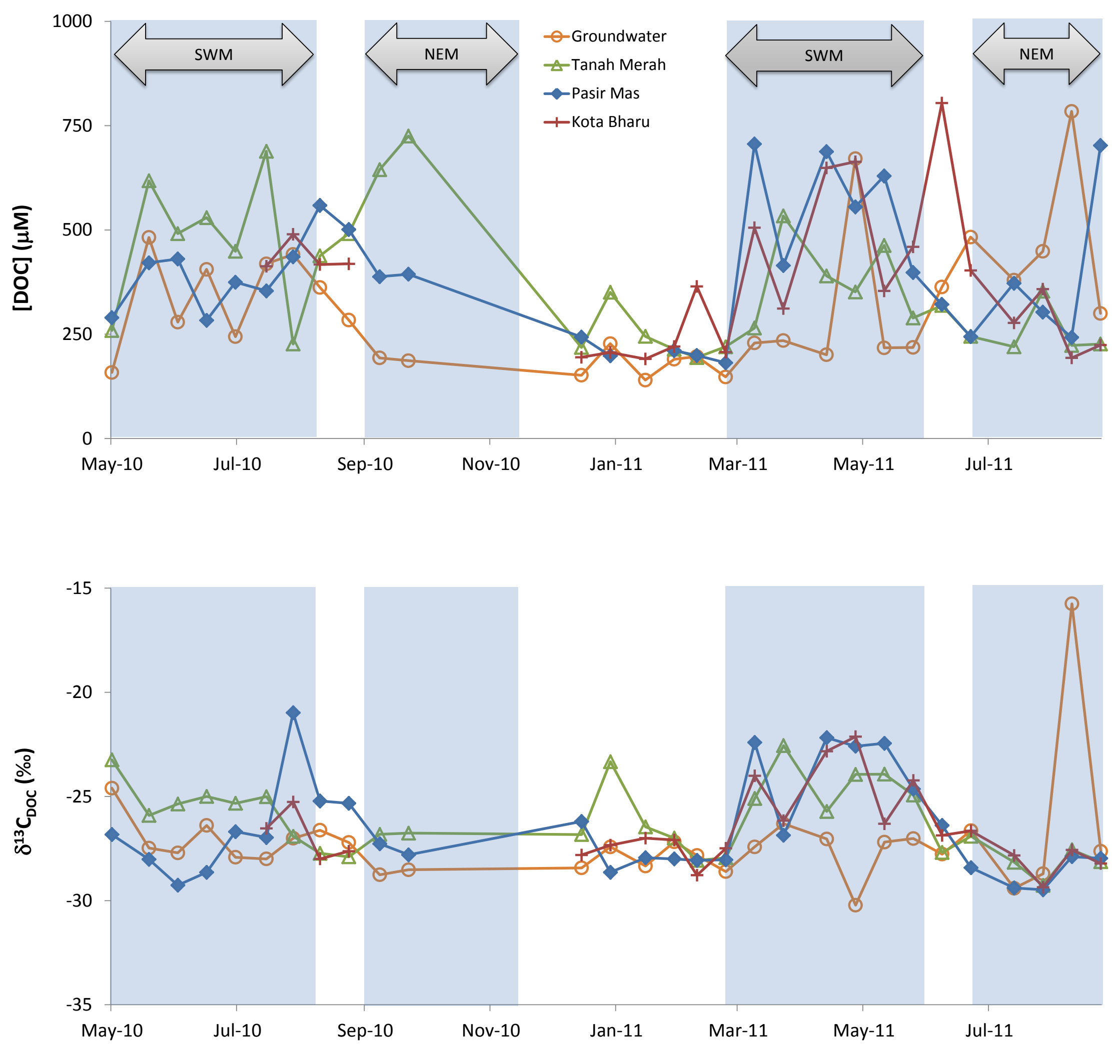


Figure 21: Temporal [DOC] and $\delta^{13}C_{DOC}$ trends in the Kelantan Basin. See appendix 4 for data.

3.2.2 $\delta^{13}C_{DIC}$ and [DIC]

DIC concentrations show a strong distinction between groundwater and river samples, with the former averaging 1,094 ± 582 μM (table 9). Lower concentrations are present in all riverine locations, with averages of 442 ± 255 μM, 490 ± 410 μM, and 611 ± 580 μM in Tanah Merah, Pasir Mas and Kota Bharu, respectively. Groundwater samples show consistently higher [DIC] during most periods, with the exception of the interval of late June 2011 to late September 2011 (fig. 22). Similar trends are present across all sites, with low [DIC] values observed from early July to late August 2010 and maxima present during early and late July 2011.

The $\delta^{13}C_{DIC}$ in groundwater samples are generally more ^{13}C-depleted as compared to river waters, showing an average value of -16.9 ± 3.4 ‰ (table 9). The $\delta^{13}C_{DIC}$ data across all river sites shows similar values, with an overall average of -13.7 ± 2.0 ‰. Temporal patterns are not apparent in the $\delta^{13}C_{DIC}$ data, although groundwater samples show more ^{13}C-depleted values during the period of early October 2010 to late March 2011. The most ^{13}C-enriched signatures were observed during early August to late September 2011 (fig. 22, bottom).

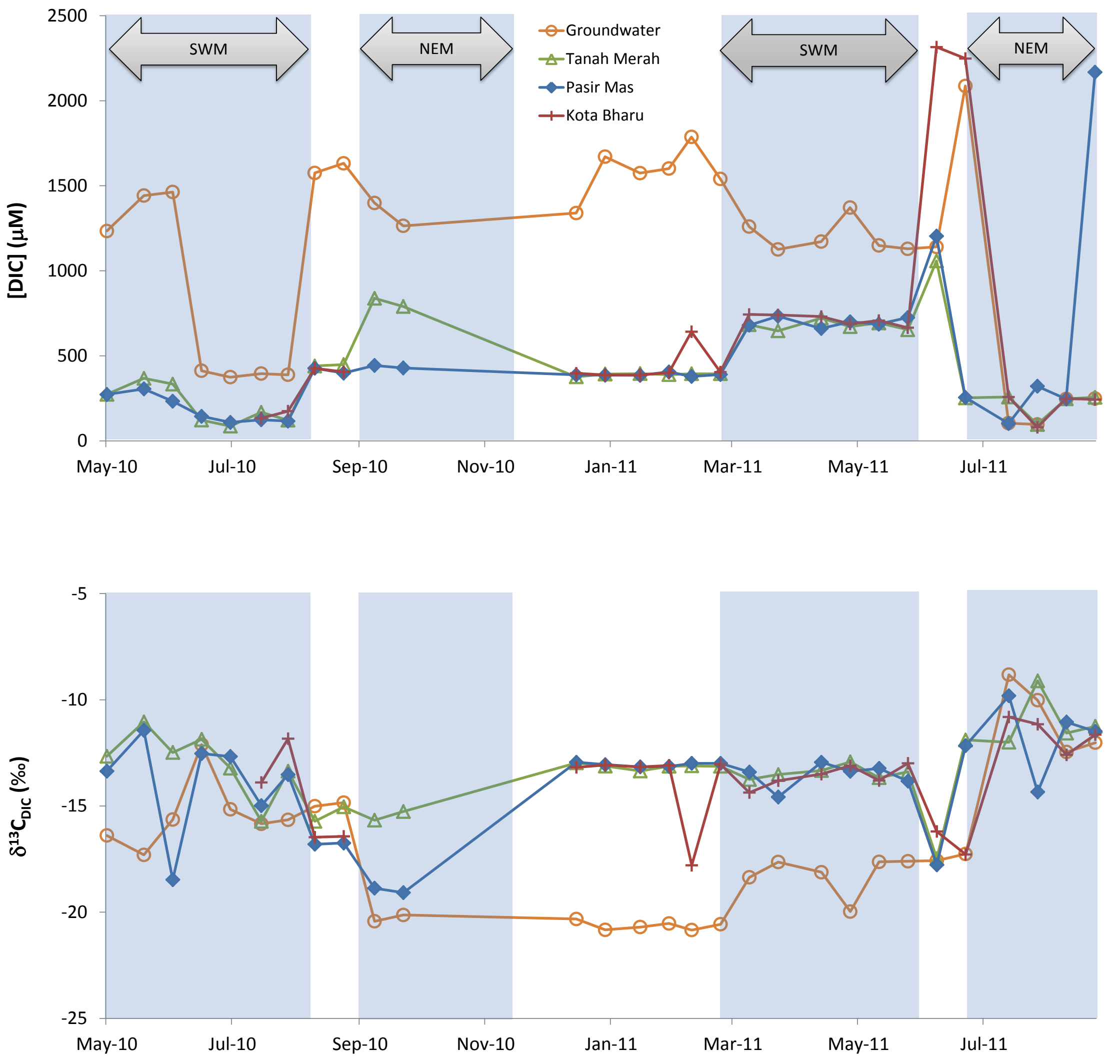


Figure 22: Temporal [DIC] and $\delta^{13}C_{DIC}$ trends in the Kelantan Basin. See appendix 4 for data.

Table 9: Summarized [DIC] and $\delta^{13}C_{DIC}$ data collected in the Kelantan Basin. Data in appendix 4.

Site	Maximum $\delta^{13}C_{DIC}$ (‰)	Minimum $\delta^{13}C_{DIC}$ (‰)	Average $\delta^{13}C_{DIC}$ (‰)	Maximum [DIC] (μM)	Minimum [DIC] (μM)	Average [DIC] (μM)
Tanah Merah	-9.1	-17.5	-13.3 ± 1.7	1058	87	442 ± 255
Pasir Mas	-9.8	-19.1	-14.0 ± 1.7	2168	102	490 ± 410
Kota Bharu	-10.8	-17.8	-13.8 ± 1.9	2315	80	611 ± 580
Groundwater	-8.8	-20.8	-16.9 ± 3.4	2086	97	1094 ± 582

3.2.3 Riverine pCO_2

Following the method outlined in section 3.1.2, pCO_2 values were calculated for all river sites in the Kelantan Basin. As riverine pH measurements were lacking for this study area, substitute data was obtained from the Malaysian Department of the Environment for the relevant years of study (see appendix 6) and the values from 2010 and 2011 were averaged over a year for each sampling location. These bulk averages were substituted into equation (8) to obtain pCO_2 concentrations in surface waters. Groundwater pH data was absent from the DOE database, precluding the calculation of pCO_2 within these samples.

Table 10: Summarized pCO_2 calculated from the Kelantan Basin data. Data in appendix 8.

Site	Maximum pCO_2 (ppmv)	Minimum pCO_2 (ppmv)	Average pCO_2 (ppmv)	Average $epCO_2$
Tanah Merah	9316	448	3329 ± 2154	8.5
Pasir Mas	19087	560	3831 ± 3756	9.8
Kota Bharu	20385	668	5487 ± 5382	14

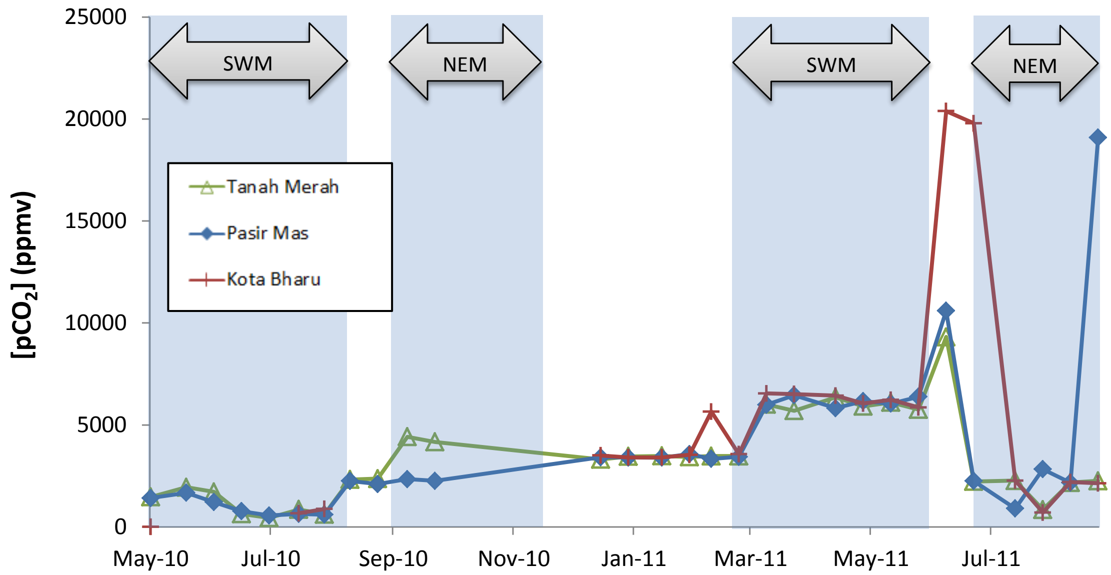


Figure 23: Temporal trends of pCO_2 partial pressure in the Kelantan Basin.

The results show CO_2 super-saturation in the Kelantan River during all sampling periods similar in magnitude to those in the Dengkil Sub-basin, with $epCO_2$ ranging from 1.1 to 52.3 (table 10, fig. 23). Averaged values are highest in Kota Bharu, with the lowest present in the upriver site of Tanah Merah, although all these localities are within the downstream section of the river (see figs. 8 and 11). All sites show strong temporal variation, with the lowest pCO_2 values observed during July to August of 2010 and 2011, and higher values observed during May to June and August to December of 2010 and 2011.

3.2.4 River Chemistry Data

The dominant element present in the river waters appears site dependent, with chloride having the largest concentrations in Pasir Mas and all other sites showing the dominance of sodium. Magnesium is present in the lowest concentrations regardless of location. DIC concentrations are the highest in groundwater, while displaying similar concentrations in the river samples (table 11, fig. 24). Temporal variability in the concentrations of these species is strong and there are no distinct common patterns, albeit there appear to be generally higher concentrations of all constituents during March to June in both 2010 and 2011 (figs. 25, 26 and 27).

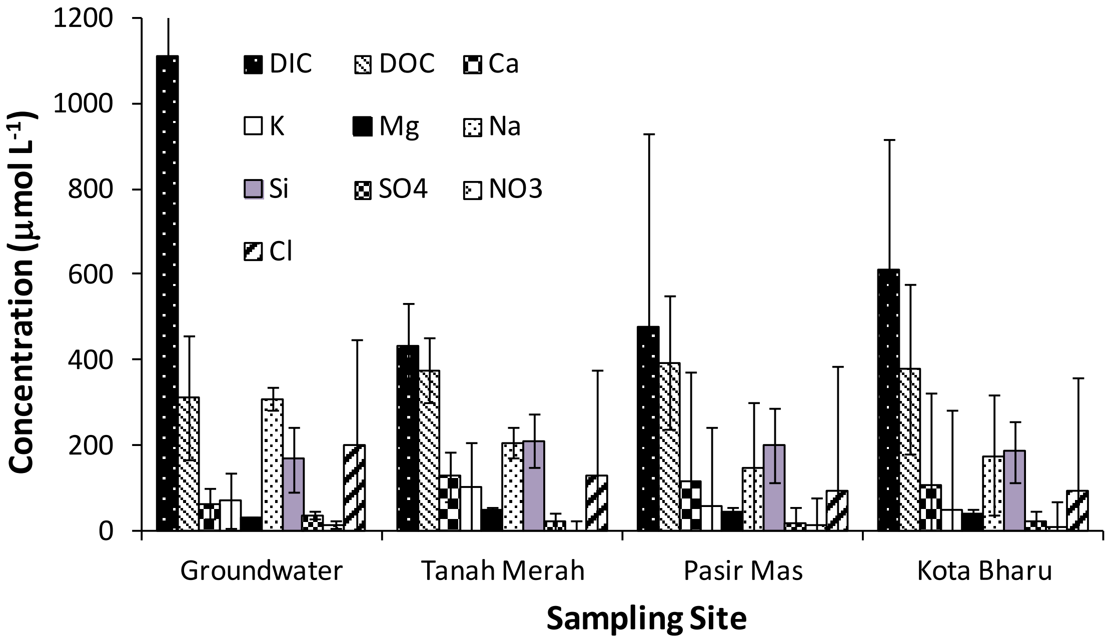


Figure 24: Averaged DIC/DOC data and selected anion/cation concentrations in the Kelantan Basin. Data in appendix 4. Error bars represent ± 1 standard deviation.

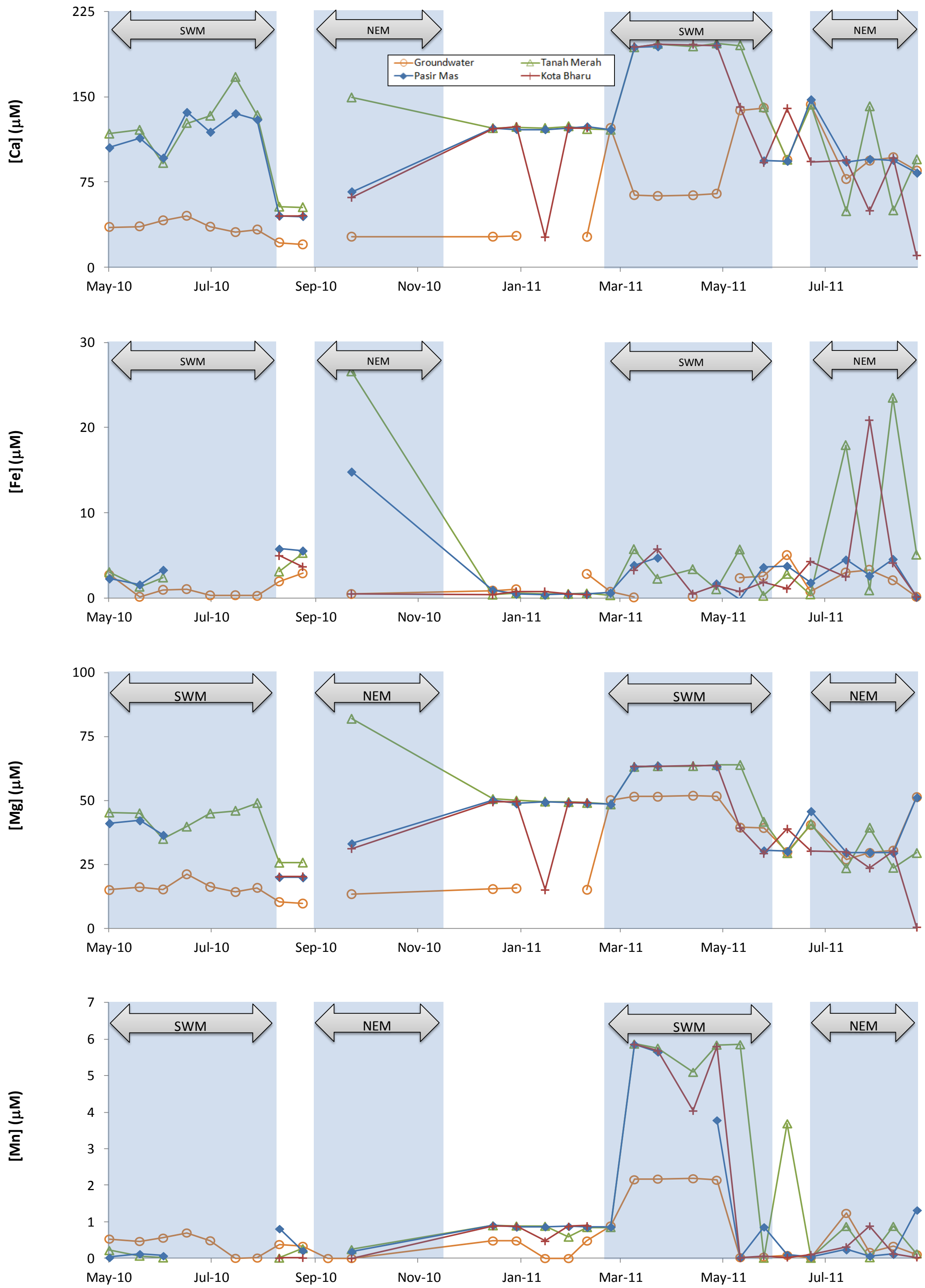


Figure 25: Temporal plots for Ca, Fe, Mg, and Mn in the Kelantan Basin. Data in appendix 4.

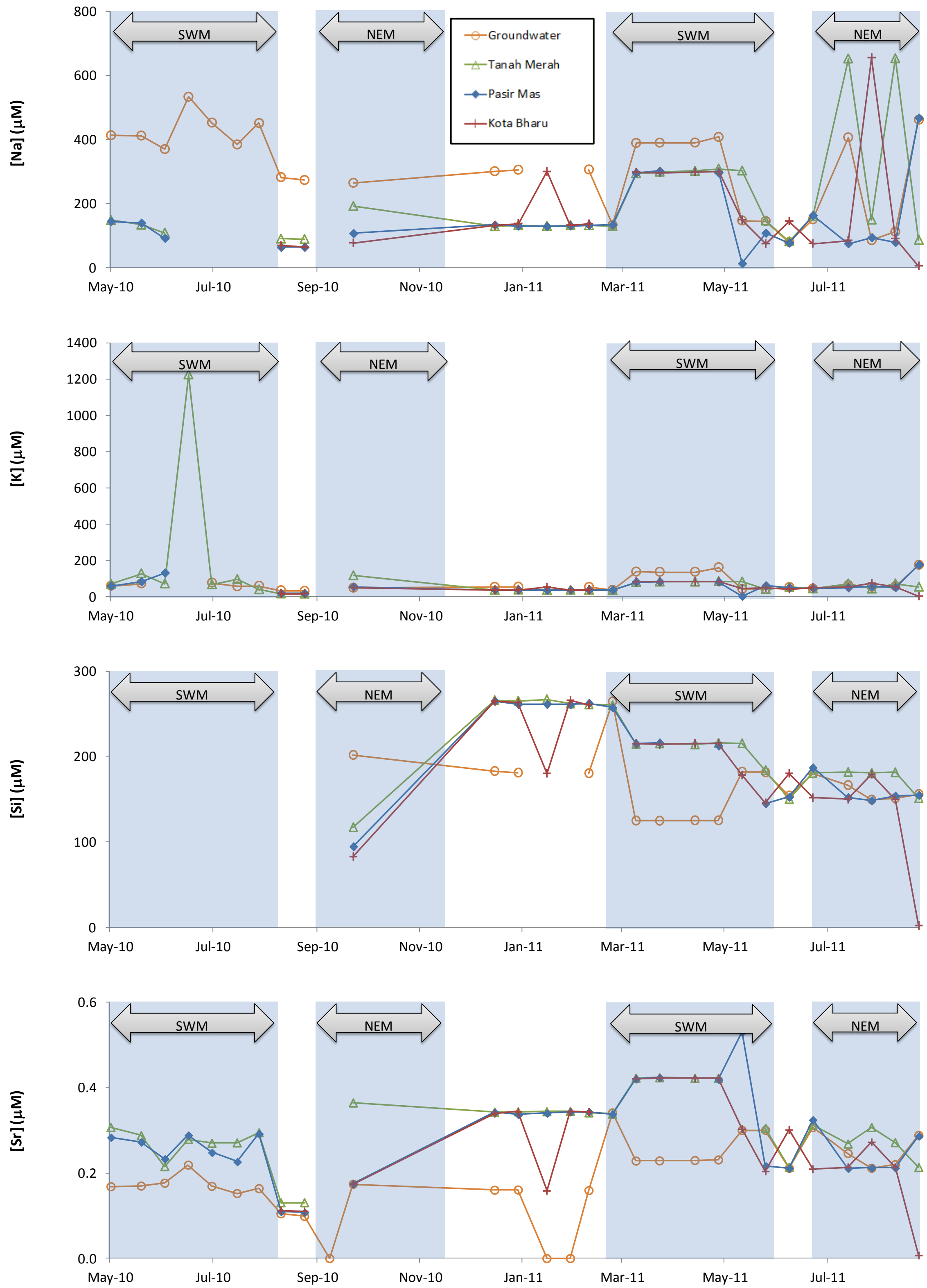


Figure 26: Temporal plots for Na, K, Si and Sr in the Kelantan Basin. Data in appendix 4.

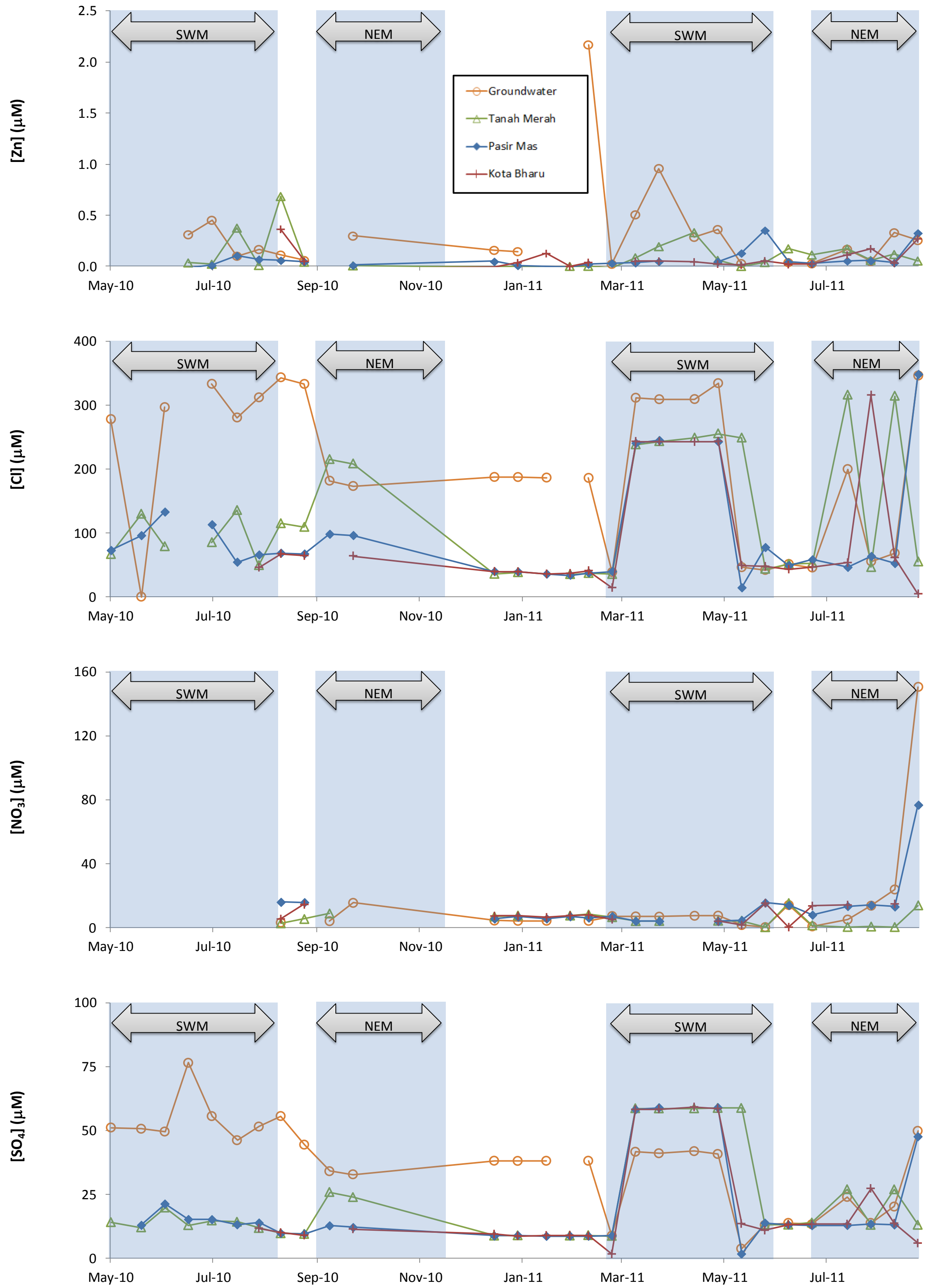


Figure 27: Temporal plots for Zn, Cl, NO_3 and SO_4 in the Kelantan Basin. Data in appendix 4.

Table 11: Yearly averaged DIC/DOC and selected water quality data in the Kelantan Basin, ± 1 standard deviation. Data in appendices 4 and 6.

Constituent [mM]	*Groundwater*	*Tanah Merah*	*Pasir Mas*	*Kota Bharu*
[DIC]	1111.1 ± 565.3	433.7 ± 248.1	476.7 ± 407.1	610.5 ± 565.3
[DOC]	311.6 ± 157.7	372.1 ± 160.0	394.3 ± 157.0	378.4 ± 157.7
[Ca^{+}]	63.4 ± 39.5	127.4 ± 44.2	115.5 ± 38.6	108.1 ± 58.0
[Fe^{3+}]	1.5 ± 1.3	4.7 ± 7.3	2.9 ± 3.2	2.9 ± 4.6
[Mg^{2+}]	28.3 ± 15.5	45.7 ± 14.3	41.9 ± 13.1	37.9 ± 18.1
[Mn^{2+}]	0.11 ± 0.2	1.66 ± 2.2	1.1 ± 1.7	1.4 ± 2.1
[Na^{+}]	309.1 ± 132.6	207.2 ± 156.6	146.2 ± 101.9	175.6 ± 147.4
[K^{+}]	71.9± 42.4	101.0 ± 221.8	56.7 ± 37.5	48.3 ± 22.7
[Si^{4+}]	166.6 ± 35.2	209.8 ± 45.4	200.2 ± 55.4	184.2 ± 67.6
[Sr^{2+}]	0.2 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.3 ± 0.1
[Zn^{2+}]	0.3 ± 0.5	3.8 ± 18.5	0.1 ± 0.1	0.1 ± 0.1
[Cl^{-}]	201.3 ± 118.8	129.2 ± 96.6	93.7 ± 81.1	92.8 ± 93.7
[NO_3^{-}]	14.2 ± 32.6	5.3 ± 4.3	12.6 ± 16.2	8.3 ± 5.0
[SO_4^{2-}]	36.6 ± 17.2	22.4 ± 18.1	18.3 ± 16.5	19.7 ± 19.3

Using equation (11), charge balance errors calculated at each site were found to be large: 50 % in Tanah Merah, 44 % in Pasir Mas, 45 % in Kota Bharu and 22 % in groundwater. As with the Dengkil Sub-basin data, these large errors could be attributed to errors in sampling or analyses, as well as uncertainties in the calculation of HCO_3^-.

The BOD, COD and DO data collected for surface water samples from Tanah Merah and Kota Bharu show similar values and characteristics for both locations. Averaged COD concentrations are highest in both areas (average values of 13.10 ± 11.30 ppm and 12.00 ± 12.07 ppm, respectively), followed by DO (6.71 ± 0.26 ppm and 6.67 ± 0.59 ppm) and BOD (2.44 ± 1.42 ppm and 3.20 ± 1.81 ppm) (fig. 28).

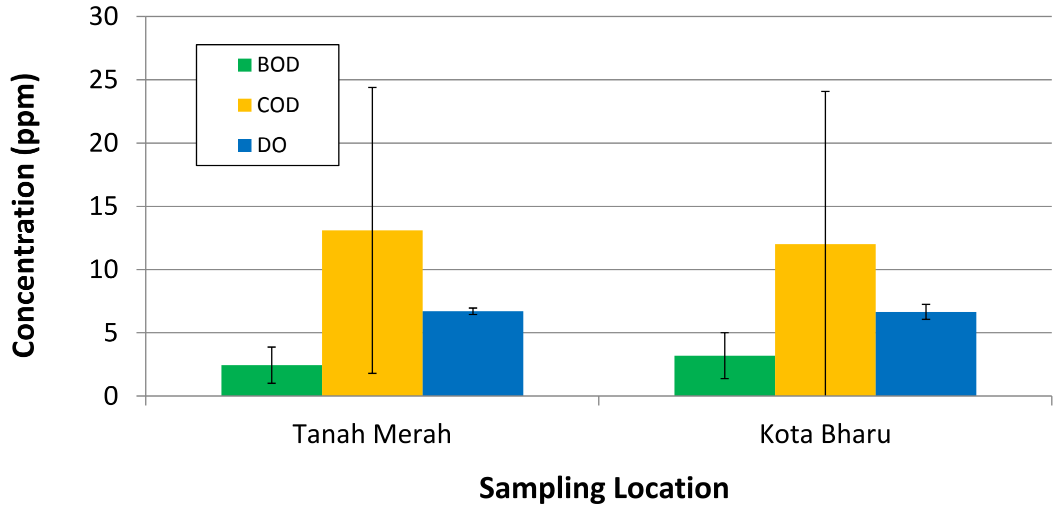
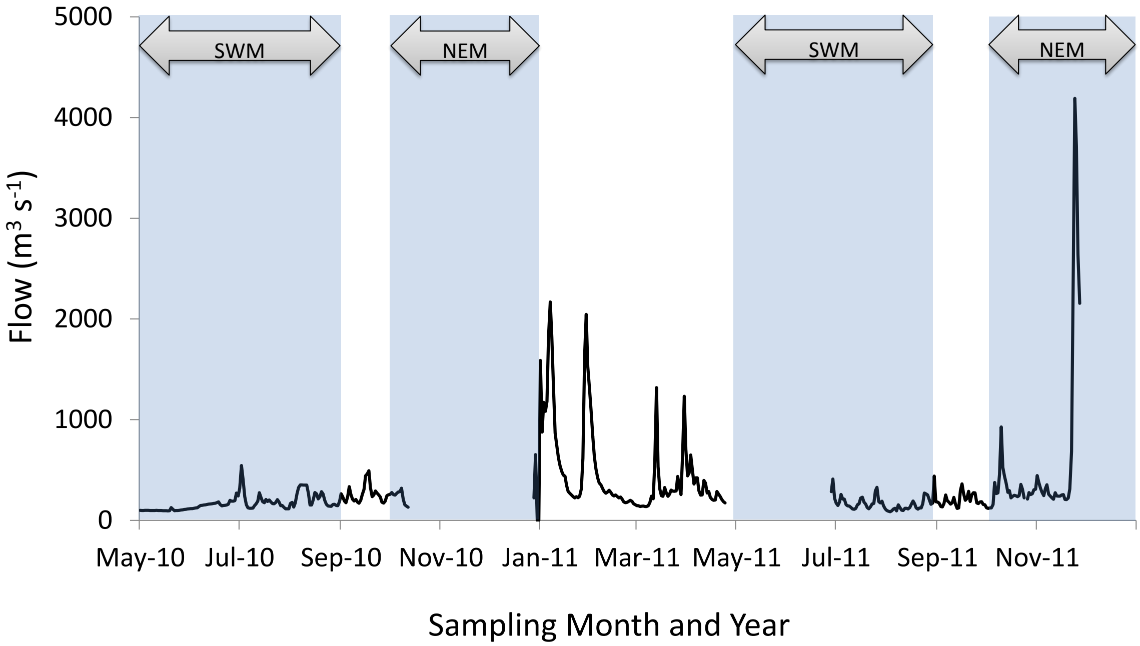


Figure 28: Averaged BOD, COD and DO values for sampling locations within the Kelantan sub-basin. Data in appendix 6. Error bars represent ± 1 standard deviation

3.2.5 Hydrology

With the data available from the Kelantan Basin, relationships between river flow and precipitation cannot be ascertained, given that the location of the river flow sampling station was upstream of the precipitation sampling location (data in appendix 13). However, a general coincidence of maximum precipitation amounts (228.9 mm on November 28, 2010) and flow rates (4,191.5 $m^3 s^{-1}$ on November 24, 2011) during the NEM is apparent (fig. 29), while the lowest flow rate of 86.6 $m^3 s^{-1}$ was observed during the inter-monsoonal interval on August 3, 2011. The impact of the SWM appears less significant than in the Langat Basin, where precipitation amounts and flow rates are somewhat higher (see section 3.1.5). This may, at least in part, be due to the rain shadow position of this basin relative to the mountainous spine of the peninsula.

a)



b)

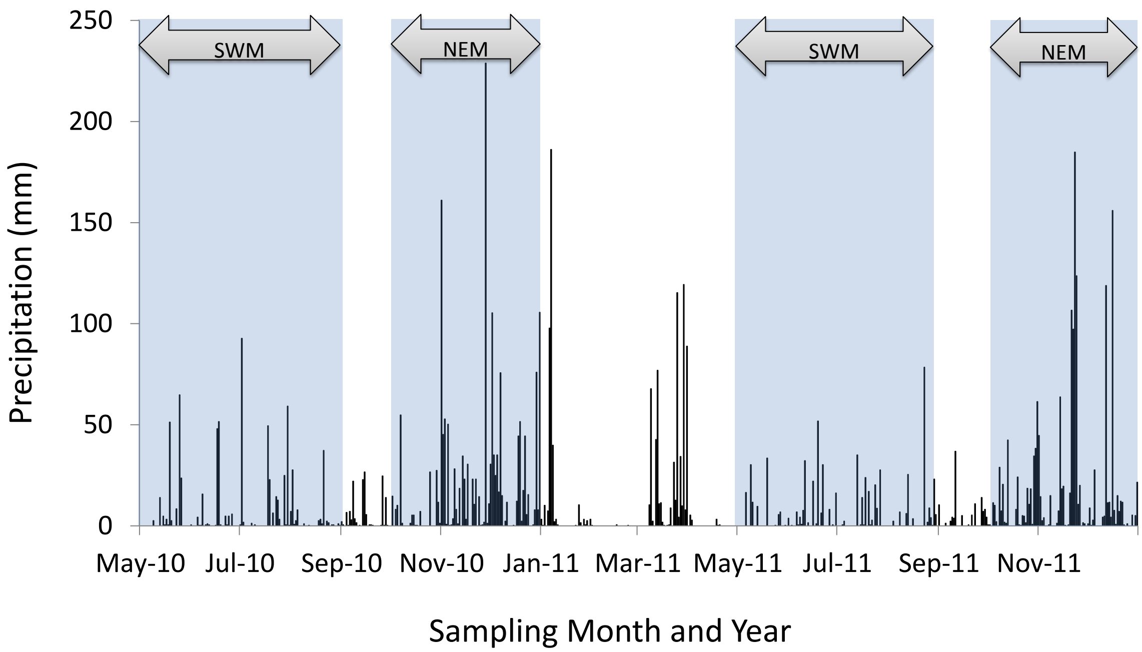


Figure 29: Plots of (a) river flow and (b) precipitation data measured at Tanah Merah station and Kota Bharu, respectively. Flow data was obtained from NAHRIM and precipitation amounts from the online NOAA database (see appendix 2 for data, and figure 11 for sampling locations).

4.0 Discussion

4.1 The Dengkil sub-basin

4.1.1 Aquatic Chemistry

To constrain the possible environmental and anthropogenic influences on carbon cycling and water chemistry in general, and to investigate the complex interplay of the above, Principal Component Analyses (PCA) were performed on all measured chemical components with the exception of phosphorous, due to the limited data available for this element, and with the addition of water temperature. PCA reduces the complexity of large multivariate datasets by explaining correlations in terms of a small number of influential factors, or principal components, allowing for easier interpretation without a significant loss of information (Davis, 1986).

PCA has been used in previous watershed studies concerned with the investigation of river pollution and water quality (Meglen, 1992; Vega et al., 1998; Helena et al., 2000). Within the Langat Basin, PCA analyses were performed by Juahir et al. (2011) on a number of water quality indicators. Their work showed strong influences from several presumed pollution sources, such as agricultural runoff, industrial inputs, and municipal waste, in additional to minor influences from mineral weathering. The distribution of the pollution sources were found to vary along the Langat River, with agriculture being a stronger influence upstream, and municipal and industrial inputs being more significant in the mid- and downstream sections.

To clarify the complicated effects of anthropogenic and natural influences on river carbon cycling in particular, all dissolved carbon concentration and $\delta^{13}C$ data were included, along with the anion, cation, TDS, water temperature and electroconductivity (EC) values. The software program used was R (R Development Core Team), an open-source statistical software package using the R programming language. This software was selected due to its relative ease of use, availability, the extensive support and resources available for the R-Programming language, and its comparable performance against other well-known statistical packages such as SPSS. Results pertaining specifically to riverine carbon cycling will be summarized briefly here, but clarified in more detail in the following sections, with the present section focusing on possible geogenic and anthropogenic influences on river water chemistry.

The river waters were analyzed with two separate PCA analyses. One was performed with all data in a single grouping and another with the data grouped separately by site, in order to determine any site-dependent differences that may exist. Groundwaters were assessed with a separate PCA from the river samples, with the omission of nitrate due to the negligible concentrations (within analytical error) that were observed during most of the sampling period.

Principal components extracted from each dataset were subject to a varimax rotation. This process further clarifies the data by decreasing the contribution of minor PCs while increasing those of more significant PCs, and results in a new set of variables known as varifactors (VF) (Vega et al., 1998). More details on the mathematics behind these PCA calculation methods can be found in Davis (1986).

Following Meglen (1992), variable loadings between 0.7 and 1.0 were considered significant, while those between 0.5 and 0.7 were considered moderate. All loadings below 0.5 were deemed to be insignificant, and are omitted from discussion. The number of selected varifactors was based on the analysis of eigenvalues via scree-plot observation, with the first VF following an abrupt change in eigenvalue chosen as the final variable.

Within groundwater (table 12, fig. 30), the first 4 VFs comprise about 55% of the total variance in the data set. The first VF showed strong loadings by Ca, Fe, Na, Sr, and Zn, with moderately positive loadings by Mg, Si and SO_4. Most of these constituents are probably derived from silicate rock weathering, but SO_4 and Zn are not representative of the silicate geology that dominates the Dengkil Sub-basin. Therefore, the latter two constituents may originate from anthropogenic contamination of the groundwater.

Based on the findings of previous studies, such sources of SO_4 include industrial and municipal wastes, fertilizers, and the burning of biomass and fossil fuels (Berner and Berner, 1996). In addition, the study by Juahir et al. (2011) suggested that zinc in house roofing may contribute to water chemistry, especially during rainfall events. Considering all of the above, this VF may represent overland flow during periods of high precipitation that later percolates down to the comparatively shallow water table. The possible influence of waste inputs in addition to rock weathering constituents may be explained by the contamination of the overland flow from the close proximity of a goat farm and its associated human housing (see section 2.2).

The second VF shows a strong positive loading by Mn, along with a weak loading by Si. While the loading by Si may represent influences from local bedrock, the Mn may be derived from pollution inputs. Previous studies in the Langat Basin have associated high levels of Mn with point source pollution sources such as leachate from waste disposal sites, sewage outflow, and industrial effluent (Hassan et al., 2011; Juahir et al., 2011). These may subsequently infiltrate into shallow aquifers and affect groundwater chemistry (Ashraf et al., 2013).

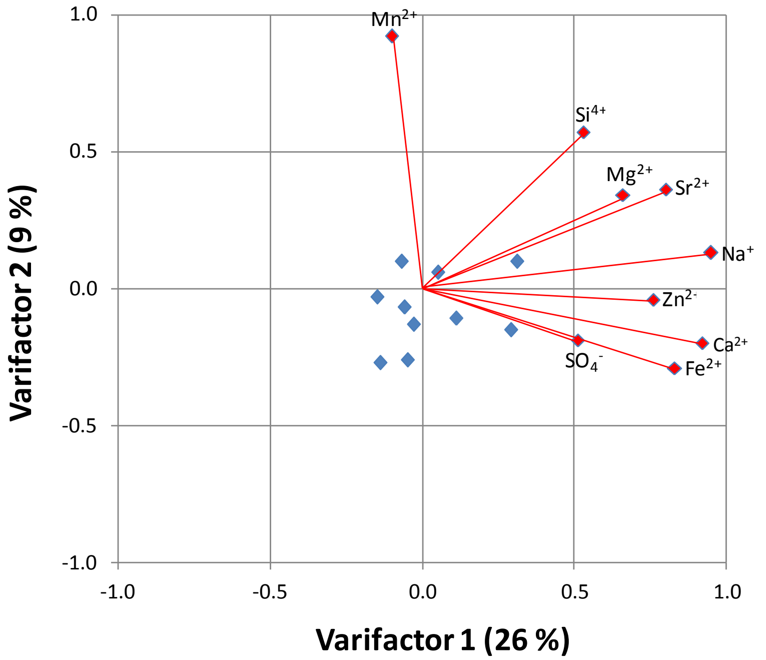
A strong positive loading by temperature exists in the third VF, along with a moderately positive loading in EC. The reason for this is uncertain, but it may be related to variations in precipitation, which acts to dilute the ionic concentrations of river waters and simultaneously affect temperature. Despite the subterranean nature of the groundwater, the relatively shallow depth of the aquifer may render these waters susceptible to influences from ambient temperatures and the chemistry of surface runoff.

In the fourth VF, a strong positive loading by $\delta^{13}C_{DIC}$ is associated with a moderately negative loading by [DIC]. This is likely associated with organic influences on DIC cycling and will be discussed further in subsequent sections (4.1.3 and 4.2.3).

Table 12: PCA results for chemical consituents in groundwater and river waters, with moderate to strong loadings in bold. Source data in appendix 3.

Parameters	Groundwater				Langat River and Tributaries				
	VF1	VF2	VF3	VF4	VF1	VF2	VF3	VF4	VF5
$\delta^{13}C_{DOC}$	-0.05	-0.26	0.05	0.10	-0.09	-0.03	-0.05	0.07	0.13
$\delta^{13}C_{DIC}$	0.05	0.06	0.04	**0.97**	-0.18	0.03	-0.11	-0.06	-0.01
[DOC]	0.29	-0.15	0.07	-0.04	-0.10	-0.01	-0.04	0.06	0.02
[DIC]	-0.14	-0.27	0.17	**-0.69**	0.39	0.15	-0.02	0.35	0.22
[Ca]	**0.92**	-0.20	-0.10	0.00	**0.90**	0.07	-0.03	0.05	0.00
[Cl]	0.11	-0.11	0.02	-0.12	0.08	**0.94**	-0.08	0.10	0.06
[Fe]	**0.83**	-0.29	-0.22	0.01	-0.01	-0.07	**0.77**	0.15	-0.19
[K]	-0.06	-0.07	0.09	0.08	0.23	**0.90**	-0.13	-0.03	-0.01
[Mg]	**0.66**	0.34	0.23	0.01	0.03	0.05	0.09	**0.98**	0.05
Mn	-0.10	**0.92**	-0.11	0.12	**0.93**	0.01	0.19	0.02	0.02
[Na]	**0.95**	0.13	-0.05	0.10	**0.92**	0.13	-0.08	0.02	0.12
[NO_3]	N/A	N/A	N/A	N/A	**0.62**	0.03	-0.11	-0.08	0.17
[Si]	**0.53**	**0.57**	0.10	0.28	**0.68**	0.14	0.14	0.06	-0.16
[SO4]	**0.51**	-0.19	-0.04	-0.04	**0.51**	0.07	-0.16	0.09	0.11
[Sr]	**0.80**	0.36	0.07	0.05	**0.97**	0.12	0.05	0.00	0.03
[Zn]	**0.76**	-0.04	-0.21	0.04	0.10	-0.15	**0.95**	0.02	-0.11
EC	-0.03	-0.13	**0.65**	-0.03	-0.14	0.07	-0.10	-0.04	0.08
pH	0.31	0.10	-0.11	0.10	-0.10	0.10	-0.08	-0.04	-0.09
TDS	-0.07	0.10	0.15	0.04	-0.12	0.16	0.02	0.02	-0.05
Temperature	-0.15	-0.03	**0.98**	-0.01	0.09	0.04	-0.21	0.07	**0.94**
Cumulative Variance Explained	0.26	0.35	0.44	0.52	0.25	0.34	0.42	0.48	0.54

a)



b)

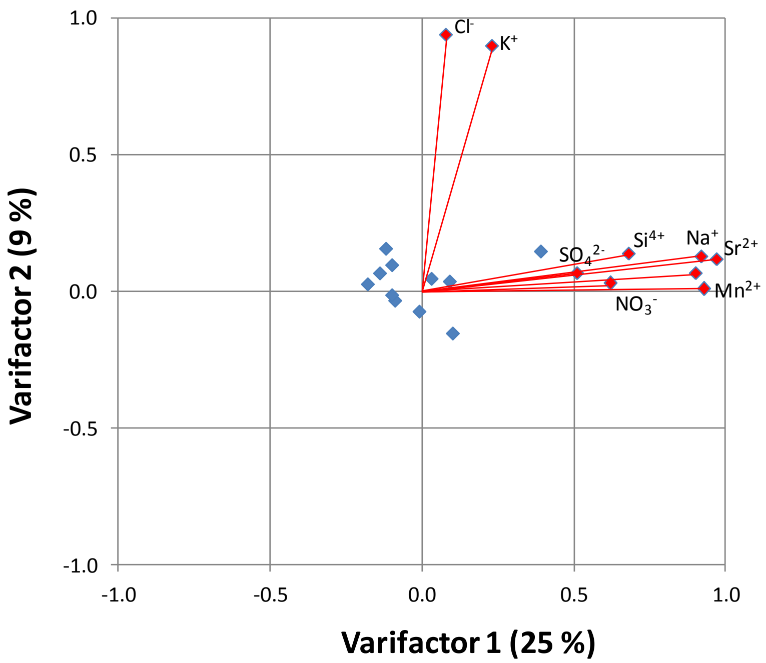


Figure 30: Dengkil Sub-basin PCA biplots for the groundwater (a) and riverine (b) sites

The river water PCAs showed that, apart from minor local differences, the same varifactors are present whether the river site data are assessed by location, or combined in a single analysis. Therefore, the PCA of the combined dataset will be discussed here, with the individual site PCA results summarized briefly and available for reference in appendices 9 and 10.

Screeplot analysis of the riverine PCA extracts the first five varifactors that explain 54 % of the total variance (table 12, fig. 30). In the first VF, there are strong positive loadings by Ca, Mn, Na and Sr, along with weaker positive loadings by NO_3, SO_4, Si and Sr. As with groundwater, these loadings are suggestive of local geology, with some overlay by pollution inputs such as sewage and industrial effluent.

The second VF shows strong positive loadings by K and Cl, which is likely indicative of agricultural runoff: in Malaysia, the most ubiquitous fertilizer types are potash-based, with the use of potassium chloride being particularly common (FAO, 2004). This is due to the importance of potassium to oil palm growth, for which significant amounts of this nutrient are needed.

Strong positive loadings by Fe and Zn are present in the third VF, which appears to be related to soil leaching and overland flow. As suggested previously, the Zn loading may be derived from the leaching of metal house roofs, with subsequent transport to the river waters via surface runoff. The fourth and fifth varifactors show only single loadings each, by Mg and temperature, respectively; these may be statistical artifacts, as their significance is otherwise unclear.

The site PCAs show varifactors that are largely identical to those obtained from the combined river dataset (appendices 9 and 10), although minor differences do exist.

One is the association of K and Cl loadings with DIC at Kajang, and DOC at Semenyih. Another difference is seen at Dengkil, which shows a varifactor with significant loadings by [DOC] and $\delta^{13}C_{DOC}$. In addition, single components related to DIC and DOC are present in all sites: Pangsun ([DOC]), Kajang ([DOC] and $\delta^{13}C_{DOC}$), Dengkil ($\delta^{13}C_{DIC}$) and Semenyih ($\delta^{13}C_{DOC}$ and [DIC]).

In summary, the PCA results show that the most common processes affecting river and groundwater chemistry are soil leaching, rock weathering, industrial waste discharge, sewage inputs, agricultural runoff and the local plant biota. There are variations in the distribution of these influences among the locations, with the upstream site showing a lesser strength of anthropogenically-derived loadings than in the mid and downstream sites. This is in agreement with the anion/cation measurements, which show elevated concentrations at Kajang and Dengkil, as compared to Pangsun (fig. 15).

In order to determine the nature of the anthropogenic overlay of the geogenic component, a plot of [SO_4] versus [Ca] was constructed for all Langat Basin sites (fig. 31). The graph show significant positive relationships between the two constituents, which fall into two distinct time periods: during October to April, when Ca and SO_4 show a correspondence approaching 1:1 (m = 0.88), and May to September, when the positive correlation displays a comparatively shallower slope (m = 0.40).

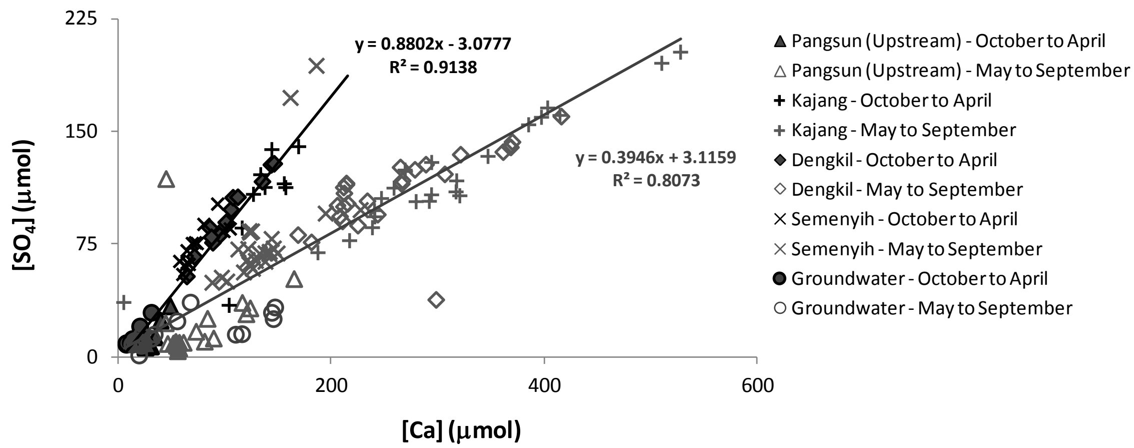


Figure 31: Plot of [SO_4] vs. [Ca] for all Dengkil sub-basin sites.

This suggests that two dominant sources of Ca influence the river chemistry, one of which is anthropogenic and the other, geogenic. The relationship observed during April to October is likely anthropogenic in nature, given the lack of naturally-occurring $CaSO_4$ in the basin geology. Such local pollution sources of $CaSO_4$ could include the use of drywall in construction projects (or the liberation of $CaSO_4$ during building demolition), agricultural utilization as soil conditioners or fertilizers, an additive in wastewater treatment, and synthetic production from industrial activities (Crangle, 2013). Conversely, geogenic Ca may be more influential during September to May, with the comparatively lower SO_4 concentrations relative to Ca indicating a lesser amount of pollution-derived inputs. The reason behind this seasonality is unclear, but it may be related to the timing and occurrence of industrial activity in the sub-basin.

The processes indicated by the PCA studies appear to have little influence on riverine carbon cycling, as shown by the lack of strong loadings by the DIC and DOC data on the relevant varifactors. While more significant loadings of DIC and DOC data are present in the individual site PCAs, these are largely decoupled from the rest of the chemical dataset.

To investigate this dichotomy, a PCA analysis was performed on [DIC], $\delta^{13}C_{DIC}$, [DOC] and $\delta^{13}C_{DOC}$. The four extracted varifactors are all single component loadings (table 13). Therefore, the dynamics of the aquatic carbon cycle in the Langat River and the Semenyih tributary is unlikely to be governed by one or two processes, but rather by a complex series of variables that will be discussed in detail in the subsequent sections.

Table 13: PCA results for dissolved carbon in river and tributary waters, with significant loadings in bold. Source data in appendix 3.

Parameters	Langat River and tributaries			
	VF1	VF2	VF3	VF4
$\delta^{13}C_{DOC}$	-0.01	0.07	**0.97**	0.25
$\delta^{13}C_{DIC}$	**0.98**	-0.20	-0.01	0.07
[DOC]	0.07	0.03	0.25	**0.97**
[DIC]	-0.20	**0.98**	0.06	0.03
Cumulative Variance Explained	27%	47%	58%	66%

4.1.2 Organic Carbon Dynamics

The $\delta^{13}C_{DOC}$ data lie within the C3 plant range, confirming the dominance of that vegetation type in the Dengkil sub-basin (figs. 32 and 33), but there are strong variations of up to 17 ‰ between minimum and maximum values (table 4). When $\delta^{13}C_{DOC}$ is plotted against [DOC], there appears to be a tendency towards more ^{13}C-enrichment, albeit still within the C3 range, with increasing concentration (fig. 33). This pattern is strongest at the downriver Dengkil site ($R^2 = 0.35$), where PCA results show significant positive loadings by $\delta^{13}C_{DOC}$ and [DOC] on the fourth varifactor (refer to appendix 10).

The lowest observed $\delta^{13}C_{DOC}$ of -35‰ to -38‰, at the highly ^{13}C-depleted tail of C3 vegetation values, are still within the range anticipated for algae, which also use the C3-pathway and have been shown to fractionate carbon by as much as 20‰ relative to riverine $\delta^{13}C_{DIC}$ values (Chanton and Lewis, 1999). These strongly ^{13}C-depleted $\delta^{13}C_{DOC}$ values were observed mostly at Pangsun, probably due to enhanced algal growth in the less turbid headwaters or in the reservoir immediately upstream.

The abundant algal growth in the upstream regions of the Langat River was confirmed by Anton (1981), who documented a greater number of algal species within the headwaters, and decreasing diversity further downstream. They attributed this reduction in algae diversity to increased turbidity in the mid- and downstream portions of the river. While this finding would agree with the ^{13}C-depleted riverine values, the occasional instance of similarly depleted $\delta^{13}C_{DOC}$ in groundwater is more difficult to explain. Given the relatively shallow depth of the local aquifer, these values could indicate infiltration of river headwaters into the groundwater or they may be an artifact of sampling and/or analytical error.

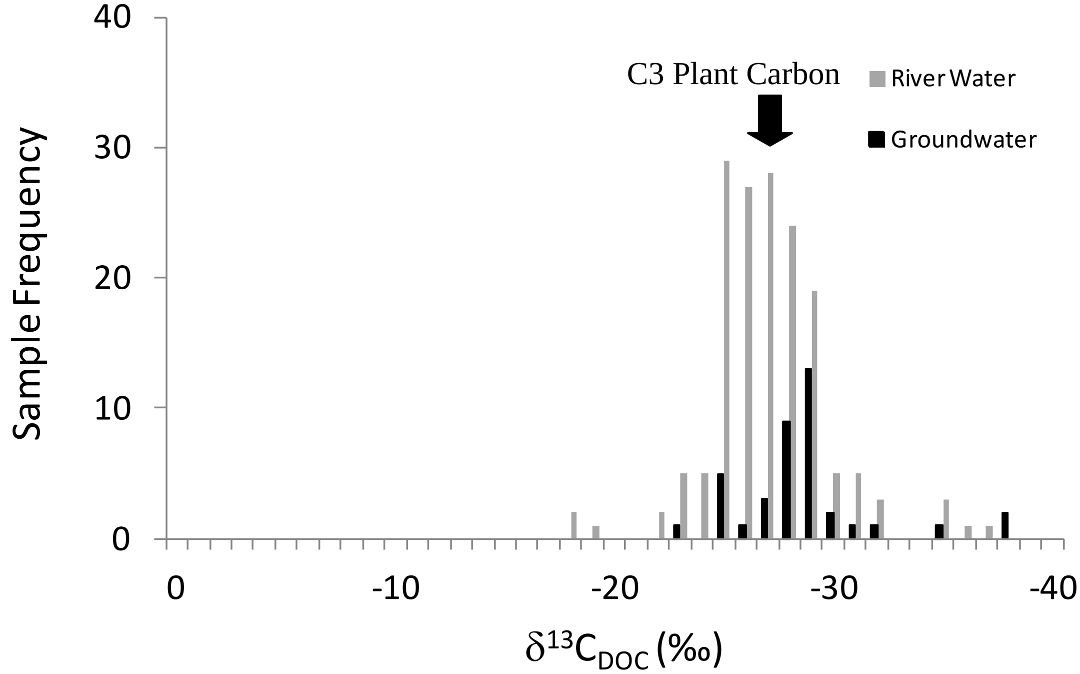


Figure 32: Histogram plot of $\delta^{13}C_{DOC}$ in the Dengkil sub-basin. Data in appendix 3.

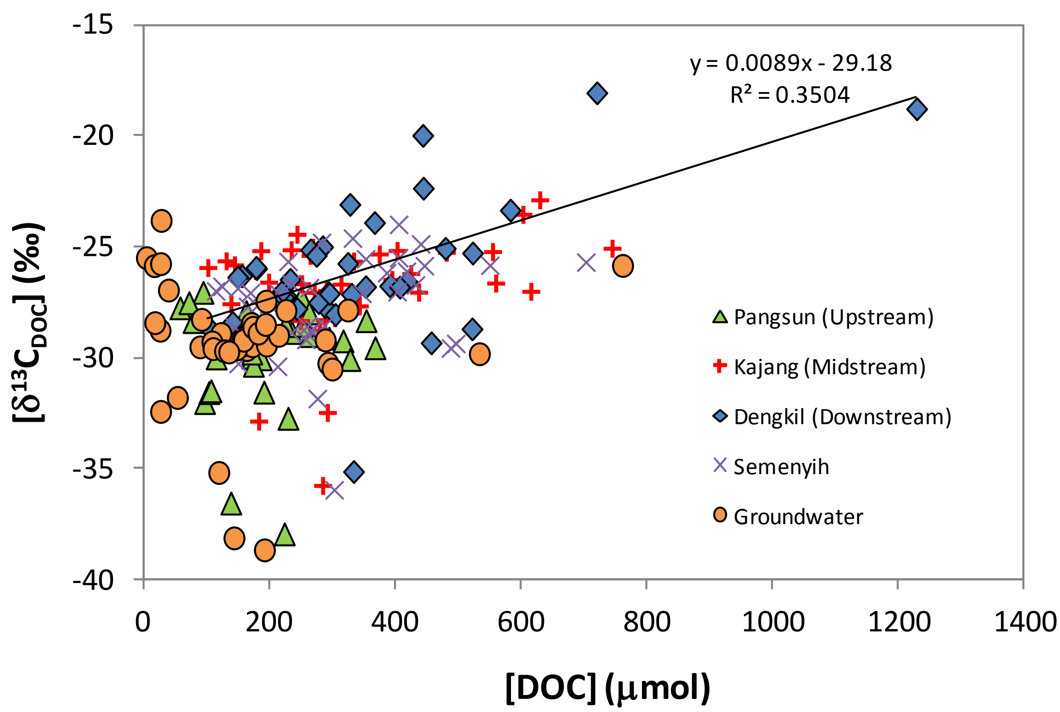


Figure 33: Plot of $\delta^{13}C_{DOC}$ vs. [DOC] for the Dengkil sub-basin. The linear regression of the downstream Dengkil data is indicated by the line and equation. Data in appendix 3.

But despite this decrease of algal diversity, DOC increases further downstream (fig. 17). The input from the Semenyih River is an unlikely source, as [DOC] in the tributary does not differ significantly from that in the Langat River. Moreover, concentrations are already elevated at Kajang, upstream of the tributary junction. An increased input of naturally-sourced DOC mid- and downstream, whether from terrestrial or aquatic vegetation, is also unlikely given the more extensive urbanization and channel modification in those areas.

With the above possibilities being improbable, the increased agricultural land cover and urbanization of the Kajang and Dengkil sites is a likely source of these elevated values, via pollution inputs. As already mentioned, sewage treatment plants and landfill sites, which are considerable repositories of human and food waste, are ubiquitous in the Langat Basin and predominate in the downstream portions of the Dengkil sub-basin (see section 2.1.2.1). The aquatic chemistry data are consistent with the enhanced pollution in this region, with elevated concentrations of pollution indicators such as BOD, COD and DO observed in the Kajang and Dengkil sites (see table 7; figs. 15 and 19).

While direct measurements are unavailable, large volumes of organic pollutants are likely also provided by the oil palm mills present in the sub-basin, which discharge palm oil mill effluent (POME) into adjacent water bodies. Biological degradation of POME can lead to severe oxygen depletion and it is estimated that on a tonne for tonne basis, the oxygen-depleting potential of POME is up to 100 times greater than that of domestic sewage (Vincent, 1993). The sum of POME discharge, sewage effluent and landfill leachate would contain significant amounts of organic carbon, which may dominate the DOC characteristics of the Langat River.

Considering the dominance of C3-plant material in POME as well as in the Malaysian diet (i.e., rice, coconut, etc.), the $\delta^{13}C_{DOC}$ of food, human and POME wastes will therefore reflect this source and be identical to the isotope signatures of naturally derived inputs (Lee et al., 2013; appendix 4). This could also explain the trend of increasing $\delta^{13}C_{DOC}$ with [DOC], as the relatively small amounts of ^{13}C-depleted DOC produced via algae production would be over-printed by the much larger contributions from terrestrial C3 plant-derived pollution sources that have more conventional C3 values. Moreover, direct DOC inputs can arise also from the plant litter of palm oil plantations that predominate in the mid- and downstream portion of the study area. Research by Moore et al. (2013) showed that tropical peatlands cleared for palm oil cultivation generated higher riverine organic carbon fluxes than undisturbed areas, due to enhanced inputs of plant material.

Influences on carbon cycling from other pollution sources, such as industrial and fertilizer inputs, are likely minimal given the lack of a relationship between concentrations of K, Cl, SO_4 and NO_3 with the DOC dataset (refer to section 4.1.1). The relationship between DOC and organic pollution inputs may also explain some of the strong temporal variation in [DOC] and $\delta^{13}C_{DOC}$, which may partly correspond to changes in pollution discharge rather than variances in environmental and climatic factors. To clarify the temporal variations seen in the DOC data (see sections 3.1.1) and the environmental and anthropogenic influences that may affect these trends, [DOC] and $\delta^{13}C_{DOC}$ were compared to river flow rates collected from the Dengkil station.

These plots, however, show minimal correlations between river flow and both [DOC] and $\delta^{13}C_{DOC}$ variations (R^2 of 0.02 and 8.0 x 10^{-5}, respectively), suggesting that DOC concentrations in the river system are largely decoupled from flow rates (fig. 34). The predominantly anthropogenic source of DOC at the Dengkil site, which would vary independently of climatic or environmental variables, may explain this lack of correlation. Note, nevertheless, some correspondence in peak and low values in both flow and ^{13}C-content are occasionally present. Higher frequency monitoring may be required to clarify this issue further.

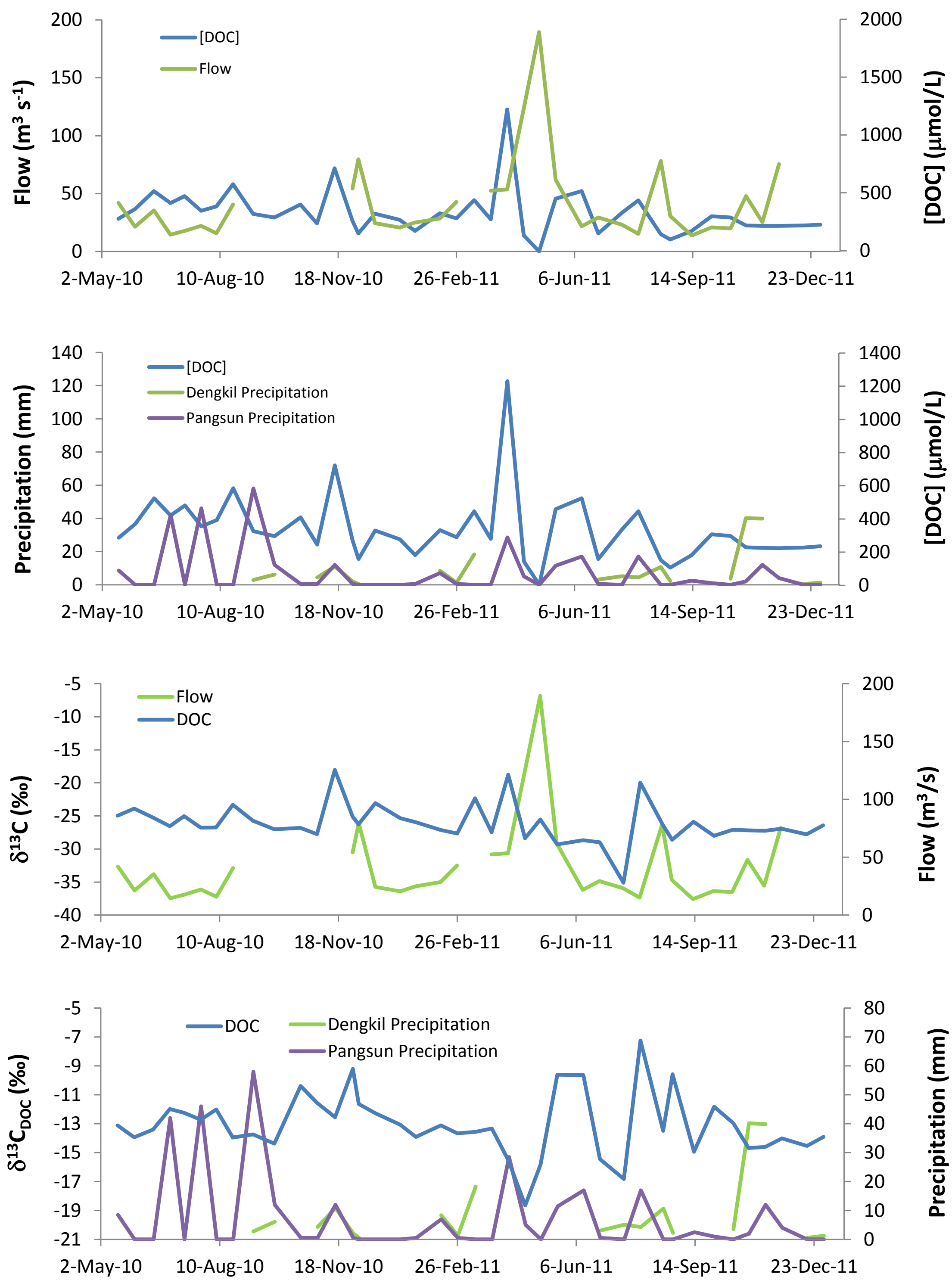


Figure 34: River flow rates and precipitation as compared to [DOC] and $\delta^{13}C_{DOC}$ at Dengkil station.

The sporadic availability of the precipitation dataset from Dengkil precludes any comparison between rainfall amounts at that site with the DOC data. Utilizing instead the more complete Pangsun precipitation records, there is no significant relationship with either [DOC] or $\delta^{13}C_{DOC}$ (R^2 of 0.16 and 0.06 for [DOC] and $\delta^{13}C_{DOC}$, respectively; fig. 34). In spite of a lack of statistical correspondence, however, the largest [DOC] values and the most ^{13}C-enriched $\delta^{13}C_{DOC}$ are often associated with peaks in precipitation levels, and depleted signatures and reduced [DOC] with lower precipitation amounts.

These relationships could be due to increased inputs of terrestrial organic carbon during rainfall events, which may dominate over the comparatively ^{13}C-depleted signatures of in-situ riverine DOC derived from algae. The latter may be of greater relative importance at times when precipitation, and thus the influence of soil-derived terrestrial DOC inputs, is minimal. In addition, increased sunlight during periods of low cloud cover could further promote algal growth via enhanced rates of photosynthetic activity.

Another possibility is that amplified fluxes of anthropogenic carbon, derived from adjacent municipal waste dumps and washed into the river by rainwater, may also be a complementary factor to the observed ^{13}C-enrichment during periods of high precipitation. As shown by Mohammadzadeh and Clark (2008) in the Ottawa region, the DOC in older landfill areas, where organic carbon has been subject to further processing, are ^{13}C-enriched relative to the expected C3 values. DOC from older landfill and waste sites in the Langat Basin are also likely to be modified in a similar way, acting to enrich the remaining DOC pool in ^{13}C via bacterial consumption.

The above data show that environmental variables may only have a minor impact on DOC cycling in the Langat Basin, as attested by poor correlations between the DOC and climate datasets, with anthropogenic pollution having a stronger influence on riverine carbon.

4.1.3 Inorganic Carbon Dynamics

The DIC data agrees with the DOC measurements in suggesting the dominance of biologically-derived carbon inputs, as supported by $\delta^{13}C_{DIC}$ values that are ^{13}C-depleted relative to expected carbonate or atmospheric signatures, and well within the range of C3 vegetation in groundwater (fig. 35). Additionally, a general trend of increasing [DIC] with decreasing $\delta^{13}C_{DIC}$ is present, as expected in environments where biological DIC sources predominate (fig. 36). This observation is supported by the PCA analyses of groundwaters (table 12).

DOC and DIC dynamics appear to be nevertheless uncoupled within the main stem of the Langat River, as documented by the absence of correlations between $\delta^{13}C_{DIC}$ and [DOC] (fig. 37) and the single variable PCA loadings (tables 12 and 13). This suggests that the DIC within the river waters are derived mainly from biologically-respired sources.

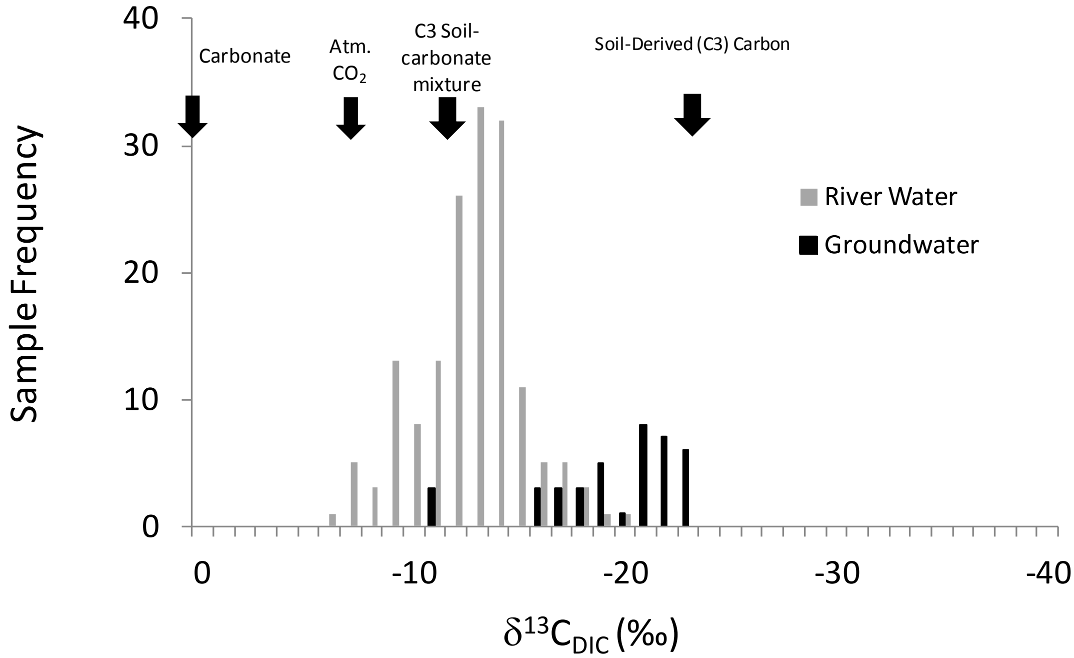


Figure 35: Histogram plot of $\delta^{13}C_{DIC}$ in the Dengkil sub-basin. Data for indicator arrows from Clark and Fritz (1997), and Dubois et al. (2010). Source data in appendix 3.

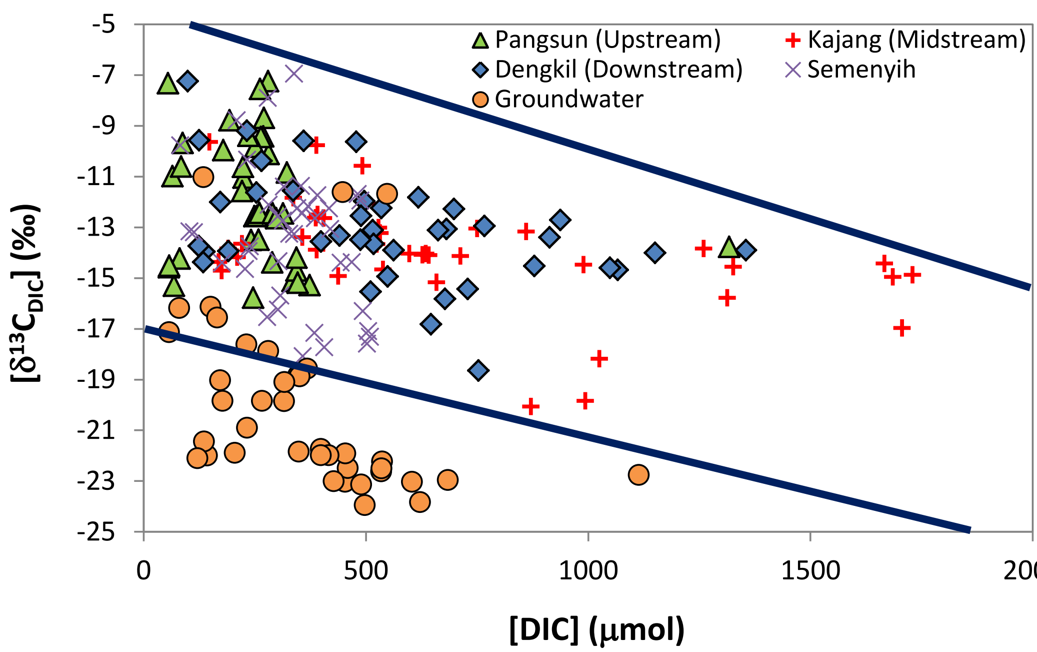


Figure 36: Plot of $\delta^{13}C_{DIC}$ vs. [DIC] for the Dengkil sub-basin. Solid lines bracket general ranges of riverine values. Data as in appendix 3.

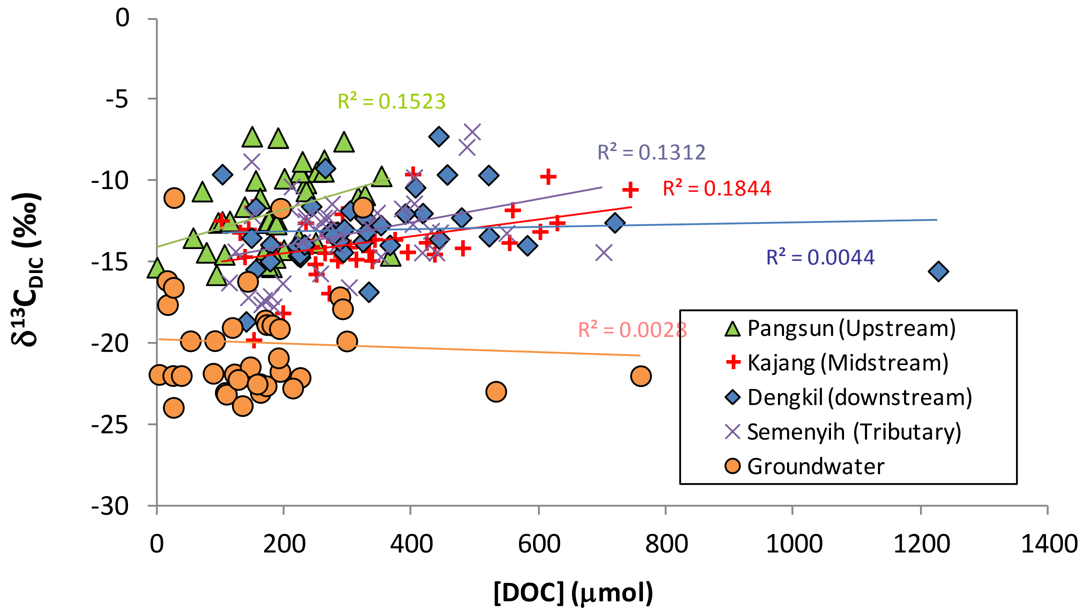


Figure 37: $\delta^{13}C_{DIC}$ versus [DOC] for the Dengkil Sub-basin. Data as in appendix 3.

Given that $\delta^{13}C_{DIC}$ values of river waters are mostly about 10 ‰ enriched relative to the expected C3-derived soil carbonate value of ~ -23 ‰ (fig. 35), additional processes must modify the riverine DIC. These may include 1) exchange of atmospheric CO_2 with river waters, 2) weathering of carbonate minerals by soil-derived carbonic acid, 3) fractionation via DIC speciation and loss, 4) photosynthetic uptake, 5) methanogenesis within the Langat Reservoir, and 6) preferential ^{13}C-loss due to CO_2 evasion from surface waters, with subsequent ^{13}C-enrichment of the residual riverine DIC.

The first possibility is unlikely, given the large overpressures of CO_2 in river waters relative to ambient concentrations in most locations (table 9; fig. 14). While the pCO_2 at Pangsun is similar to atmospheric values during some intervals, overall it is an order of magnitude larger, particularly in the mid- and downstream reaches. The dominant movement of CO_2 is therefore from the river waters into the atmosphere, not vice versa.

The dissolution of carbonate minerals by soil-sourced carbonic acid (no. 2), and subsequent mixing of this carbon with biologically-respired DIC, can theoretically yield the observed riverine values. Limestone outcrops are scarce in the Langat Basin (see section 2.1.2.1), but the high solubility of these rocks and the comparatively ^{13}C-enriched isotope signature of the derived marine-sourced carbonate would have a disproportionately large influence on riverine $\delta^{13}C_{DIC}$.

A plot of sodium-normalized Ca^{2+} and Mg^{2+} molar concentrations by lithologic fields (Gaillardet et al., 1999) shows that much of the data from the upstream Pangsun site clusters within, or are adjacent to, the field of silicate-dominance (fig. 38). The nearby groundwater values trend towards an evaporate-dominated field, but the known absence of any such lithology in the basin suggest alternative influences. These may include pollution inputs but it is likely that marine influences, such as sea spray and aerosol deposition, are more significant due to the proximity of all sites to the peninsular coast.

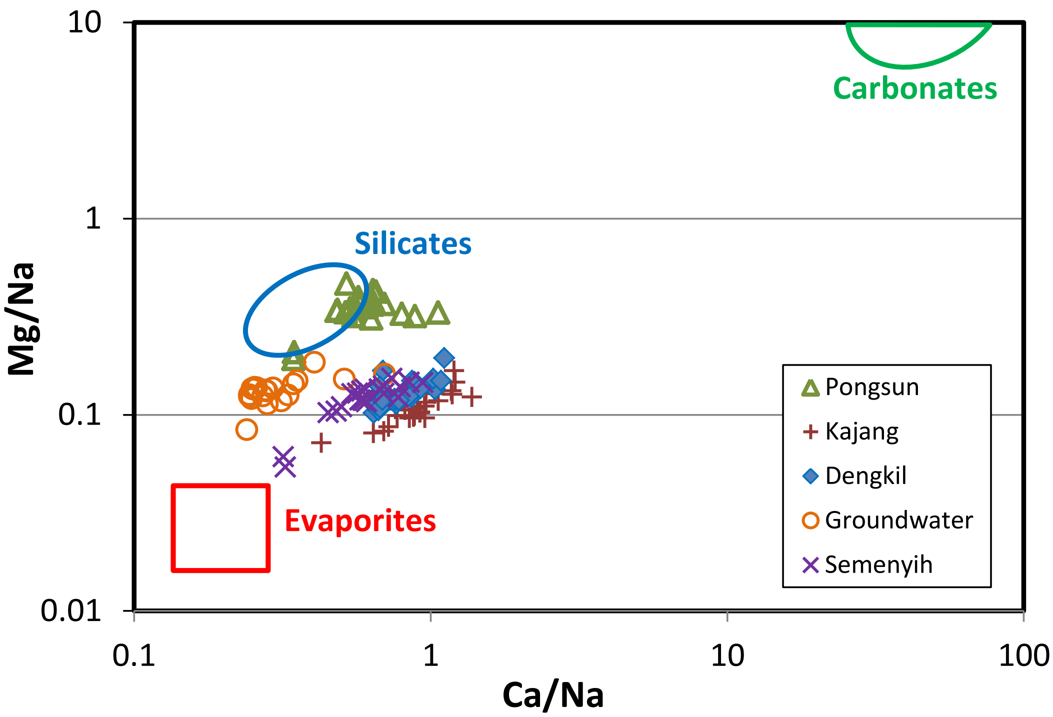


Figure 38: Plots of Mg/Na versus Ca/Na for each sampling site, using lithology fields from Gaillardet et al. (1999). Data listed in appendix 3.

In the mid- and downstream locations, and at Semenyih, the data points cluster along the carbonate-evaporite tangent, potentially suggesting a minor carbonate contribution from these sources. One can calculate such carbonate inputs by a simplified mass balance as shown below:

(11) $$C_{carb} = \frac{C_{DIC}(\delta_{DIC} - \delta_{bio})}{\delta_{carb} - \delta_{bio}}$$

Where C_{carb} represents the concentration of carbonate-derived DIC, C_{DIC} is the total DIC concentration, δ_{DIC} is the riverine $\delta^{13}C_{DIC}$ value, δ_{carb} is the $\delta^{13}C$ of carbonate-derived

DIC (likely to be around 0‰ for marine-derived carbonate sourced from local limestone) and δ_{bio} is the $\delta^{13}C$ of biologically-respired DIC (assumed to be -23‰). Equation (11) is a simplification which assumes that only biologically-respired and carbonate-derived DIC contribute to the riverine pool, disregarding isotope fractionation via DIC utlization by photosynthetic or methanogenic activity.

Nonetheless, this exercise shows (table 14) that unreasonably large percentages (40 - 50 %) of carbonate inputs would be needed to explain the observed $\delta^{13}C_{DIC}$ values in surface waters. In contrast, for groundwaters, where the expected influence of carbonate geology should be strongest, the estimated percentage is only 13%.

The above considerations argue that the importance of carbonate minerals as a primary DIC source is minor, supporting the notion that pollution inputs may be at least partially responsible for the spread of geochemical data outside the lithology fields. As mentioned, marine-sourced NaCl may be an additional influence acting to skew the distribution of data points towards the evaporate-dominated region.

Table 14: Summarized percentages of theoretical carbonate inputs to riverine DIC calculated from the Dengkil Sub-basin data.

Site	Maximum % Carbonate	Minimum % Carbonate	Average % Carbonate
Pangsun	68.5	31.4	48.7 ± 10.5
Kajang	58.1	12.8	39.9 ± 8.8
Dengkil	68.5	18.9	43.4 ± 9.6
Semenyih	69.8	21.4	42.4 ± 11.4
Groundwater	52.1	0.0	13.2 ± 14.6

The speciation of DIC (hypothesis no. 3) could theoretically yield a fractionation factor that can explain the observed ^{13}C-enrichment: the pH data indicate a dominance of H_2CO_3 within groundwater, while surface waters show the prevalence of HCO_3^-. The equilibrium fractionation for the dissociation of H_2CO_3 within the temperature conditions observed in the Dengkil sub-basin is about 9 ‰, based on the following equation (Clark and Fritz, 1997):

(12) $$10^3 \ln \alpha^{13}{}_{HCO3-CO2(aq)} = 9.866(10^3 T^{-1}) - 24.12$$

Adding this to the basin-wide averaged $\delta^{13}C_{DIC}$ of -13 ‰, yields a value of -22 ‰, similar to the expected $\delta^{13}C_{CO2}$ value of the original soil-derived input.

However, the continuous input from the soil source would require also a continuous mechanism of HCO_3^- loss from the river water, otherwise the bulk $\delta^{13}C_{DIC}$ would remain unchanged and similar to expected C3 plant-derived soil values. This necessary DIC loss can, however, achieved by CO_2 degassing. This alternative is a strong possibility given the calculated CO_2 overpressures in the surface waters of the Langat River (see table 6 and fig. 16), and will be discussed in more detail later in the text.

As already mentioned, enhanced photosynthetic activity (hypothesis no. 4) is a possibility for the upstream Pangsun site, a proposition consistent with the more ^{13}C-depleted $\delta^{13}C_{DOC}$ signatures of this site as compared to the mid- and downstream locales. The comparatively low pCO_2 at Pangsun, which occasionally approach atmospheric levels, is also consistent with such a scenario. However, the increased turbidity further downstream would likely impedes primary production, yet the $\delta^{13}C_{DIC}$ signatures are still ^{13}C-enriched, by as much as 20‰ relative to the average C3 soil carbonate value.

I therefore propose that photosynthetic activity of any significant impact would likely be confined to the headwaters of the Langat River and to the adjacent reservoir, but exert negligible influences on DIC cycling further downstream. The observed CO_2 overpressures, increased BOD and reduced DO in the downstream sites relative to Pangsun are also consistent with such interpretations. Note, nevertheless, that even in the headwaters, pCO_2 is much higher than ambient levels during most of the year. The photosynthetic explanation can thus be rejected as a dominant factor behind the ^{13}C-enrichment of DIC. By process of elimination, methanogenic activity (No. 5) in the Langat Reservoir and high rates of CO_2 efflux from the water surface (No. 6), driven by over-pressurization, remain as the most likely mechanisms for isotopic fractionation of riverine DIC.

In the case of CO_2 evasion (No. 6), the ^{13}C-depleted CO_2 would be preferentially degassed relative to ^{13}C. This is due to the kinetic isotope fractionation that occurs during the aforementioned process of HCO_3^- dehydration to CO_2 and the subsequent loss of CO_2 gas, resulting in a ^{13}C-enriched residual DIC pool. This has been observed in earlier carbon isotope studies of riverine DIC cycling at similar pCO_2 overpressures (Doctor, 2008). In order to test this hypothesis, a Rayleigh fractionation equation is used to estimate the $\delta^{13}C$ for riverine DIC sourced from organic carbon:

(13) $$\delta^{13}C_{DIC} = \delta^{13}C_{resp} - \varepsilon[\ln(f_{rem})]$$

In the above, $\delta^{13}C_{DIC}$ represents the averaged riverine value for the period of November 2010 to December 2011, $\delta^{13}C_{resp}$ is the presumed isotope value of soil-respired carbon, f_{rem} is the remaining fraction of DIC in the river waters following degassing, and ε represents the fractionation factor associated with the conversion of HCO_3^- (assumed dominant in riverine waters, given the observed pH range) into gaseous CO_2 according to the following formula:

(14) $$\varepsilon^{13}C_{HCO_3-CO_{2(g)}} = 9.551(10^3T^{-1}) - 24.10$$

Rearranging (13) to solve for $\delta^{13}C_{resp}$, results in -22.2 ‰ for the presumed source CO_2 within the Langat Basin, a value identical to that expected from C3 soil-derived CO_2. The hypothesis that CO_2 outgassing can explain the observed ^{13}C-enrichment of riverine DIC relative to C3-sourced carbon is therefore a realistic proposition.

In the upstream site, there is a possibility that methanogenesis (No. 5) is active, given the location's proximity to the Langat Reservoir. Previous studies have confirmed the ubiquity of CH_4 production in large reservoirs and lakes, with high outgassing rates measured not just in lake reservoirs, but also in streams located immediately downstream of these water bodies. For example, research carried out by Guérin et al. (2006) in French Guyana and Brazil showed that outgassing rates of both CO_2 and CH_4, driven by supersaturation of these gases within surface waters, were higher in streams as compared to their source reservoirs.

While in the present study no direct measurements of methane were made, it can be assumed that any methanogenic activity would have been accompanied by a ^{13}C-

enrichment of the DIC pool by up to 40 ‰ to 60 ‰, depending on the mechanism involved (Whiticar et al., 1986). Due to these large fractionations, even a small amount of methanogenic activity can have a large effect on the bulk $\delta^{13}C_{DIC}$, as shown by Gu et al. (2004) for a Florida lake, where ^{13}C-enriched DIC was associated with large CH_4 concentrations in lake waters and sediments.

Theoretically, methanogenesis may, alone or together with enhanced photosynthetic activity, explain some of the ^{13}C-enriched DIC, particularly at the upstream site. This methane production would likely occur in the anoxic reservoir sediment, utilizing DIC as a substrate to produce ^{13}C-depleted CH_4 and ^{13}C-enriched CO_2 (Nissenbaum et al., 1972; Stiller and Magaritz, 1974). The ^{13}C-enriched DIC from the sediment pore waters would then enter the water column and be discharged into the river headwaters immediately downstream of the reservoir. Unfortunately, due to the absence of direct measurements of CH_4 concentrations and evasion fluxes, the significance of such methanogenic activity remains largely unknown.

Accepting the dehydration of HCO_3^- and subsequent CO_2 evasion to be the dominant in-river process, progressive CO_2 outgassing in the mid- and downstream portions of the Langat River should result in declining [DIC] and increasing $\delta^{13}C_{DIC}$ values down river. Yet, the opposite trend is observed, with the mid- and downstream reaches having elevated [DIC] and pCO_2, and comparatively ^{13}C-depleted $\delta^{13}C_{DIC}$ when compared to the upstream and groundwater sites.

Some of this trend could be due to the outgassing of CO_2 from the Langat Reservoir itself, prior to discharge of its waters into the river headwaters. Previous surveys of lake-sourced river headwaters have shown lower DIC concentrations and higher $\delta^{13}C_{DIC}$ compared to downstream areas, due to extended periods of gas evasion resulting from long residence times of waters in the lakes (Barth and Veizer, 1999; Brunet et al., 2005; Guérin et al., 2006; Abril et al., 2005).

Nevertheless, as with DOC, much of the increased DIC concentrations in the mid and downstream reaches of the sub-basin are most likely due to enhanced anthropogenic carbon inputs. Note that concentrations of elemental constituents are also higher within the same locations, despite the fact that there are no major geological changes that could result in increased inputs of either dissolved chemical species or DIC in the mid- and downstream sections.

The organic carbon input provided by POME discharge, sewage effluent and landfill leachate would undergo reprocessing and isotopic fractionation due to CO_2 outgassing, as with natural inputs. This is evident at Kajang and Dengkil, where $\delta^{13}C_{DIC}$ becomes more ^{13}C-depleted with increasing [DIC] (fig. 34). In contrast, the upstream site shows that isotopic fractionation of natural inputs is evidently already accomplished either in the soil zone or in the source reservoir, prior to discharge into the headwaters.

As with DOC, the DIC data are compared to rainfall and river flow data in order to evaluate the influence of natural environmental factors on temporal variations in DIC inputs, relative to the effects of pollution discharge. The resulting plots show that peak flow values generally coincide with [DIC] maxima, suggesting that river flow may have some influence on riverine DIC concentrations (fig. 39).

While relationships between flow and $\delta^{13}C_{DIC}$ are more ambiguous, many of the maxima and minima in stable isotope values correspond with peak and low flow rates. Along with the concentration data, this may suggest an increasing input of biologically-derived DIC during some periods of increased flow, while the absence of correlations during other sampling times indicates an increased importance of anthropogenic carbon inputs.

The $\delta^{13}C_{DIC}$ data appears to show a stronger correspondence with rainfall amounts from Pangsun and Dengkil, where the largest ^{13}C-depletions and excursions are associated with peak and minimum precipitation values, respectively. Relative to biological values, dissolved CO_2 in rain water would be comparatively enriched due to the minimal ^{13}C-depletion that occurs during the dissolution of atmospheric CO_2 into rain droplets (~1.1‰ at 25°C) (Mackenzie and Lerman, 2006). The addition of this precipitation-derived carbon to the river system could result in a ^{13}C-enrichment of riverine DIC, resulting in the observed association of high $\delta^{13}C_{DIC}$ values with large quantities of rain.

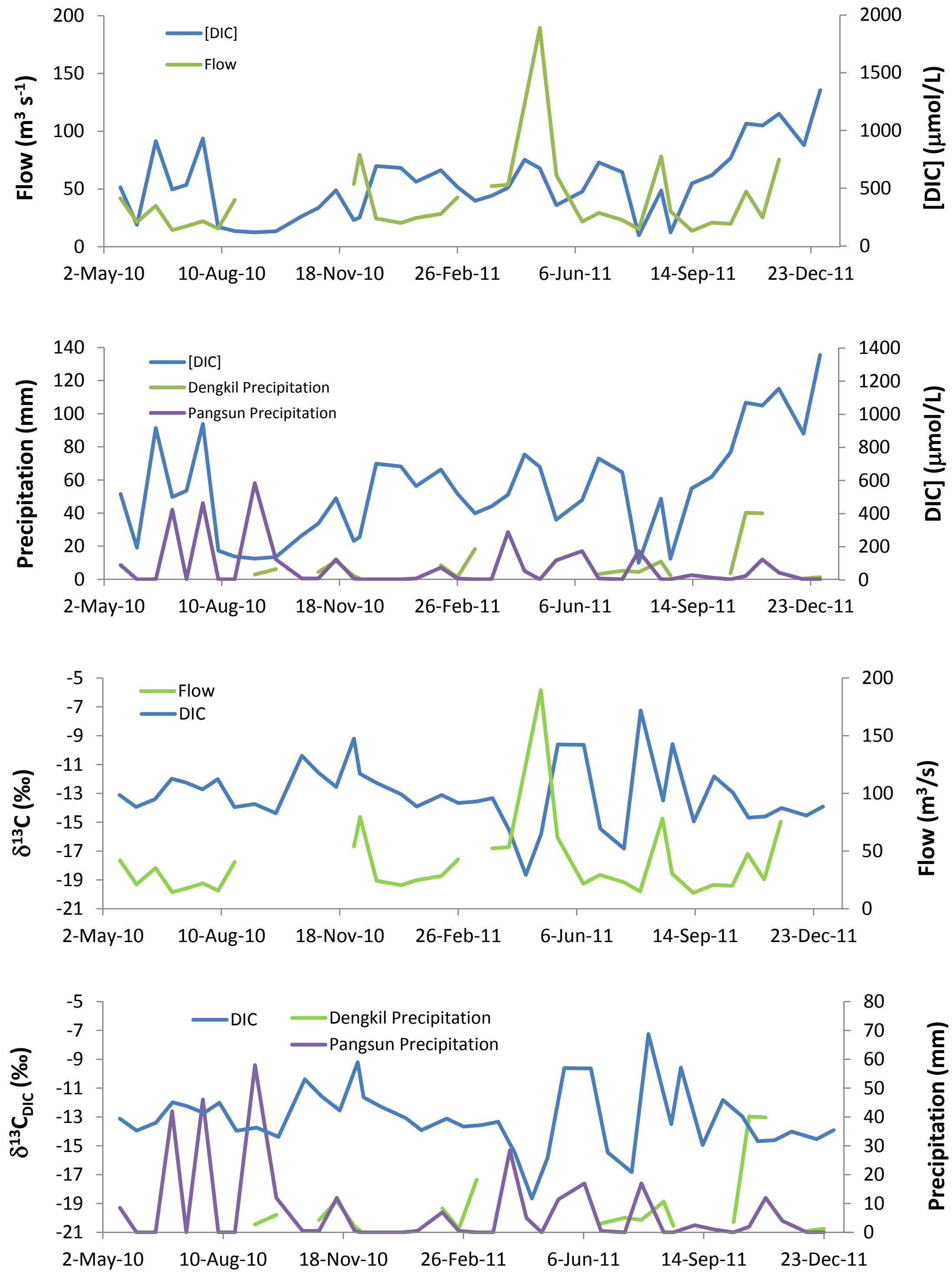


Figure 39: River flow rates and precipitation as compared to [DIC] and $\delta^{13}C_{DIC}$ at Dengkil station. Data from appendices 1 and 3.

4.1.4 Watershed Carbon Balance

Annually averaged CO_2 evasion rates from Dengkil Sub-basin water bodies were calculated by incorporating the pCO_2 data into equation (9), and averaging the resultant fluxes over the period of December 2010 to November 2011 (see appendix 7 for pCO_2 values, and appendix 1 for water temperature data). Using this method and both the lower and upper-end gas transfer coefficient values (see equation (9) and section 2.4), the annual efflux rate ranged from 1.2 kg C m^{-2} yr^{-1} (k = 1.9 m/d) to 2.4 kg C m^{-2} yr^{-1} (k = 4.0 m/d) (table 15), from which a total annual carbon export range of 19.8 x 10^3 t C yr^{-1} to 41.2 x 10^3 t C yr^{-1} was calculated by multiplying the annual efflux rate by the total water body surface area in the sub-basin, as determined by Yang et al. (2001) (see table 1).

Table 15: Calculated carbon fluxes in the Dengkil sub-basin

Carbon Fluxes	
CO_2 evasion per unit area (kg C yr^{-1} m^2): k = 1.2 m/d	1.2
Total atmospheric flux (10^3 t C yr^{-1}) : k = 1.2 m/d	19.8
CO_2 evasion per unit area (kg C yr^{-1} m^2): k = 4.0 m/d	2.4
Total atmospheric flux (10^3 t C yr^{-1}) : k = 4.0 m/d	41.2
Average DOC Export (10^3 t C yr^{-1})	8.5
Average DIC Export (10^3 t C yr^{-1})	8.9
Average POC export (10^3 t C yr^{-1})	4.3

Dissolved carbon fluxes in the Dengkil Sub-basin were calculated by multiplying the DOC and DIC data by river flow values at each sample date, with the latter being measured at the downstream site during the same day of sampling (see section 2.5 and appendix 5). The results were also averaged over the period of a year (December 2010 to November 2011) to obtain annual mean flux rates. Via these calculations, DIC and DOC fluxes were estimated at 8.9 x 10^3 t C yr^{-1} and 8.5 x 10^3 t C yr^{-1}, respectively. These values result in a combined dissolved carbon flux of 17.5 x 10^3 t C yr^{-1}.

This total flux of dissolved carbon is comparable to the lower-end estimate of annual evasive CO_2 loss, with dissolved carbon transport averaging roughly 90% of degassing losses. However, there is a strong temporal variability in the proportion of dissolved and gaseous carbon export: some sampling periods showing dissolved carbon transport being up to 6 times larger than the lower-end evasive loss estimate, while others show this evasion value being larger than dissolved carbon loss by a similar magnitude.

These large variations may be due to changes in anthropogenic carbon inputs rather than natural variation, given the lack of correspondence between the DIC data and environmental variables such as river flow and precipitation. Greater inputs of waste products from sewage, landfills and palm oil processing mills would increase rates of biological activity, and thus CO_2 production via decomposition of these inputs. Comparatively, the effects of environmental influences such as air temperature, river flow and precipitation would be less significant.

Given the lack of direct POC measurements, POC fluxes were estimated by substituting total suspended solid (TSS) data collected during 2011 by the DOE at Dengkil into the following equation (Ludwig et al., 1996):

(15) $$\text{POC\%} = -\,0.16\log\left(\text{cTSS}^3\right) + 2.83\log(cTSS^2) - 13.6\log(cTSS) + 20.3$$

In the above formula, *cTSS* is in units of mg/L. Equation (15) was based on measurements obtained from 19 rivers based in tropical, temperate and sub-arctic settings. Ludwig et al. (1996) found this formula to be the best fit for the collected data, with an *r* of 0.83.

Based on equation (15), the POC flux is 4.3 x 10^3 t C yr^{-1}. In combination with the DIC and DOC fluxes, a total carbon flux to the ocean of 21.8 x 10^3 t C yr^{-1} can be assumed. This value is comparable to the minimum mean annual estimate of carbon lost via outgassing, further highlighting the importance of CO_2 evasion as a mechanism of carbon loss from the watershed (fig. 40).

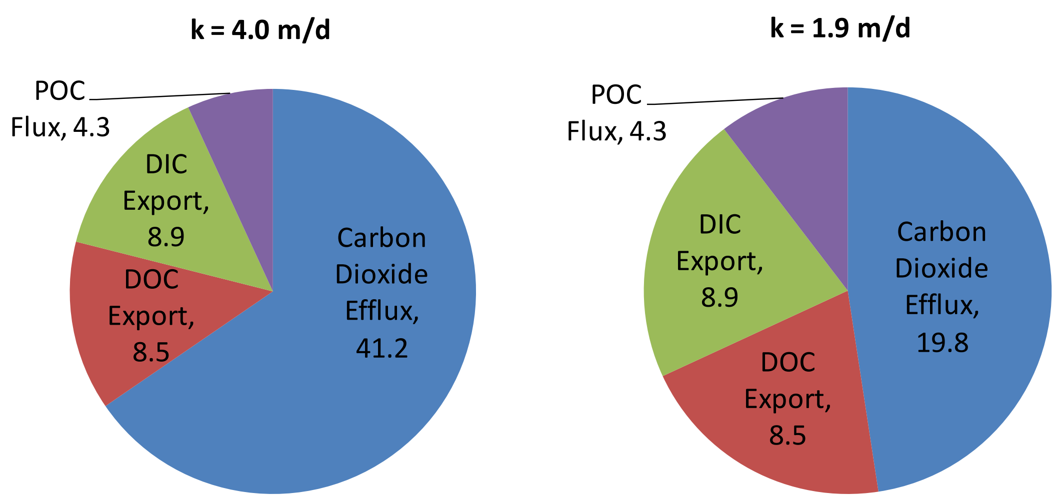


Figure 40: Summary of carbon export fluxes in the Langat Basin in 10^3 t C yr^{-1}, for upper and lower-end k estimates.

In total, the amount of carbon exported out of the basin via river transport and CO_2 outgassing ranges from 41.6 x 10^3 t C yr^{-1} to 63 x 10^3 t C yr^{-1}. These values are only about 2 % to 3 % of the estimated photosynthetic uptake of carbon within the basin, assessed to be around 1,981 x 10^3 t C yr^{-1}. The latter value was calculated from $\delta^{18}O/\delta^2H$ data collected from the same locations and incorporated into a water balance equation via a water utilization efficiency (WUE) factor (Syakir, personal communication). Therefore, riverine carbon export represents only a small portion of the total carbon loss from the watershed. As with other tropical forest ecosystems, the largest losses to the atmosphere would be via ecosystem respiration, with smaller amounts incorporated into ecosystem biomass, soils, and riverine sediments (Grace et al., 2001).

4.2 The Kelantan Basin

4.2.1 Aquatic Chemistry

PCA was performed on the Kelantan River and groundwater data, using the same methods as outlined in section 3.1.3. Due to the similarity of the downstream Kelantan River locations, as well as the comparitive paucity of measurements in each site, all riverine data were included in a single PCA. Most of the same physico-chemical variables as in the Langat Basin were used, but EC, pH, TDS and water temperature measurements were not available.

With the groundwater PCA, a lack of data during several sampling intervals required the omission of certain chemical constituents for a proper PCA analysis. The chemical species omitted (Mn, Zn and Sr) were those deemed to be less diagnostic with respect to assessment of water pollution and mineral weathering. From the results, the first 6 VFs were chosen, accounting for 92% of the total variance (table 16, fig. 41).

Table 16: PCA results for chemical consituents in the Kelantan Basin groundwater, with moderate to strong loadings in bold. Source data are in appendix 4.

Parameters	Kelantan Basin Groundwater					
	VF1	VF2	VF3	VF4	VF5	VF6
$\delta^{13}C_{DOC}$	-0.1	0.08	0.01	**0.99**	0.06	0.01
$\delta^{13}C_{DIC}$	-0.04	**0.94**	0.06	0.11	0.14	0.12
[DOC]	-0.27	0.46	-0.07	**0.73**	0.19	0.05
[DIC]	-0.07	**-0.94**	-0.04	-0.15	-0.1	-0.16
[Ca]	**-0.73**	0.13	**0.58**	0.06	-0.07	0.08
[Cl]	**0.95**	0.04	0.12	-0.13	0.2	0.15
[Fe]	**-0.54**	0.25	-0.35	-0.07	0.11	-0.07
[K]	**0.73**	0.14	0.45	-0.03	0.32	0.36
[Mg]	0.05	0.04	**0.98**	-0.03	0.04	0.13
[Na]	**0.94**	0.08	0.05	-0.21	0.02	0.07
[NO_3]	0.34	0.3	0.2	0.04	-0.03	**0.87**
[Si]	-0.37	-0.26	-0.04	-0.18	**-0.87**	0.03
[SO4]	**0.92**	-0.1	-0.14	-0.01	0.17	0.22
Cumulative Variance Explained	33%	50%	63%	76%	84%	92%

The first VF shows strong positive loadings by Cl, K, Na, and SO_4, along with a strong negative loading by Ca. Given the proximity of the groundwater site to the ocean, the association of Na, Cl and SO_4 could indicate a marine influence in the form of sea salt and dimethylsufide (DMS) deposition, while the loadings by K and Ca may be indicative of the alluvial sediment. In the second VF, there is a strong positive loading in $\delta^{13}C_{DIC}$ along with a strong negative loading in [DIC], again reflecting the dynamics of the carbon cycle: the negative correlation between concentration and $\delta^{13}C_{DIC}$ would indicate a ^{13}C-depleted biological carbon source (see section 4.1.3).

A strong positive loading by Mg is present in the third VF, along with a moderately positive loading by Ca. The influences of rock weathering may be dominating this varifactor, as these elements in conjunction are suggestive of silicate mineralogy (Berner and Berner, 1996). The fourth VF shows strong positive loadings by both $\delta^{13}C_{DOC}$ and [DOC], also a reflection of carbon dynamics. This was also observed in the

Dengkil Sub-basin DOC data, implying a dominance of terrestrially-derived organic carbon over autochthonous riverine production (see section 4.1.2).

The fifth VF shows a strongly negative loading in Si, but no other loadings of significance are apparent, suggesting that this component is related to silicate weathering. In the last VF, there is only a single strong positive loading in NO_3, which is probably derived from the agricultural fertilizers applied to cultivation in and around the river mouth.

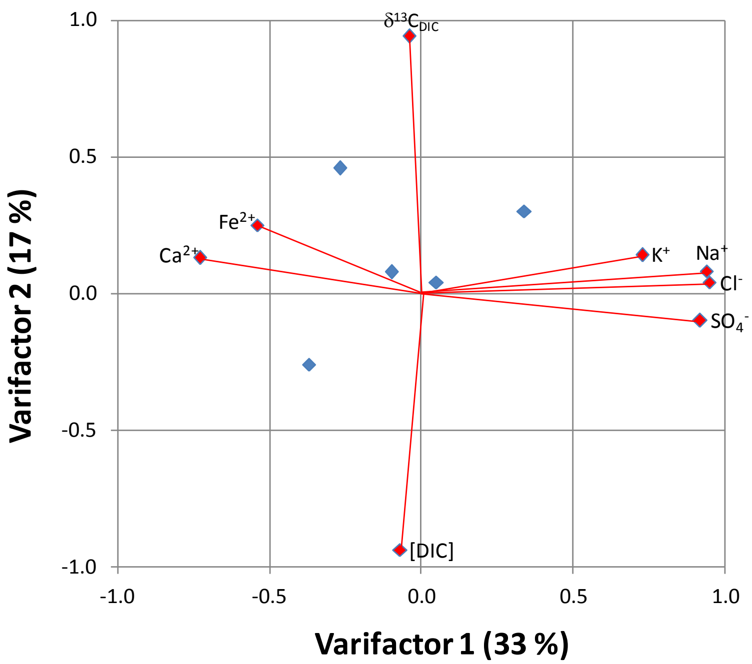
From the river PCA, the first five varifactors, making up about 72% of the total dataset variance, were selected for discussion (table 17, fig. 41). The first varifactor shows strong positive loadings by Ca, Mg, Mn and Sr, with a moderately positive loading by SO_4. These loadings suggest that this component is derived mostly from bedrock weathering, although the significance of SO_4 implies a degree of anthropogenic influence as well (see section 4.1.1).

The second VF displays strong loadings by Cl, Fe, and Na, associated with moderate loadings by K and SO_4. These variables are probably representative of anthropogenic inputs into the Kelantan River, with minor contributions from soil weathering and overland runoff. The strong loadings by Na and Cl may also represent the overlay of a marine influence.

Table 17: PCA results for chemical consituents in the Kelantan River, with moderate to strong loadings in bold. Source data are in appendix 4.

Parameters	Kelantan River				
	VF1	VF2	VF3	VF4	VF5
$\delta^{13}C_{DOC}$	0.42	0.13	-0.07	-0.01	-0.06
$\delta^{13}C_{DIC}$	0.02	0.09	0.08	0.05	**0.97**
[DOC]	0.27	0.16	0.19	-0.19	-0.11
[DIC]	0.02	0.04	0.30	-0.07	-0.34
[Ca]	**0.95**	-0.07	-0.14	-0.01	0.05
[Cl]	0.35	**0.86**	0.21	-0.11	0.04
[Fe]	-0.35	**0.75**	-0.22	-0.24	-0.12
[K]	0.24	**0.59**	0.63	-0.24	0.05
[Mg]	**0.73**	0.36	0.01	-0.02	-0.13
[Mn]	**0.92**	0.03	0.11	0.32	-0.03
[Na]	0.06	**0.96**	0.02	0.14	0.13
[NO_3]	-0.15	0.01	**0.94**	-0.03	0.07
[Si]	0.41	-0.12	-0.12	**0.86**	0.06
[SO4]	**0.66**	**0.56**	0.15	-0.21	0.01
[Sr]	**0.87**	0.17	-0.10	0.42	0.07
[Zn]	-0.14	0.30	0.33	-0.17	0.05
Cumulative Variance Explained	27%	47%	58%	66%	73%

a)



b)

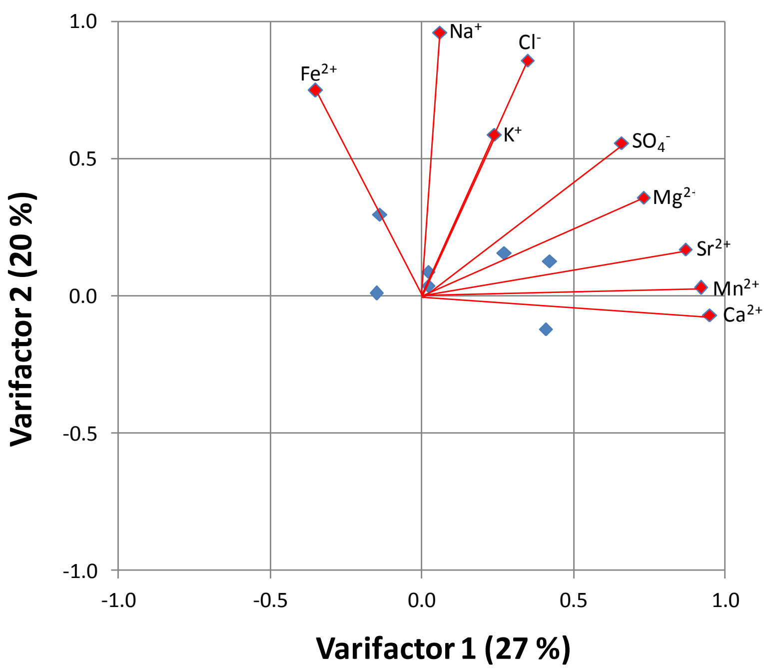


Figure 41: Kelantan Basin PCA biplots for the groundwater (a) and riverine (b) sites

In the third varifactor, there is a strong positive loading by NO_3, along with a moderately positive loading in K. These constituents are likely related to agricultural activity, and are representative of the use of nitrate and potassium-based fertilizer. A similar conclusion was reached by Ahmed et al. (1996), where high levels of nitrate were associated with Tobacco agrosystems that were prevalent in the studied river section. The fourth VF shows a strong positive loading by Si, suggesting that the influence of silicate-weathering dominates this component. In the final VF, there is only a strong positive loading by $\delta^{13}C_{DIC}$.

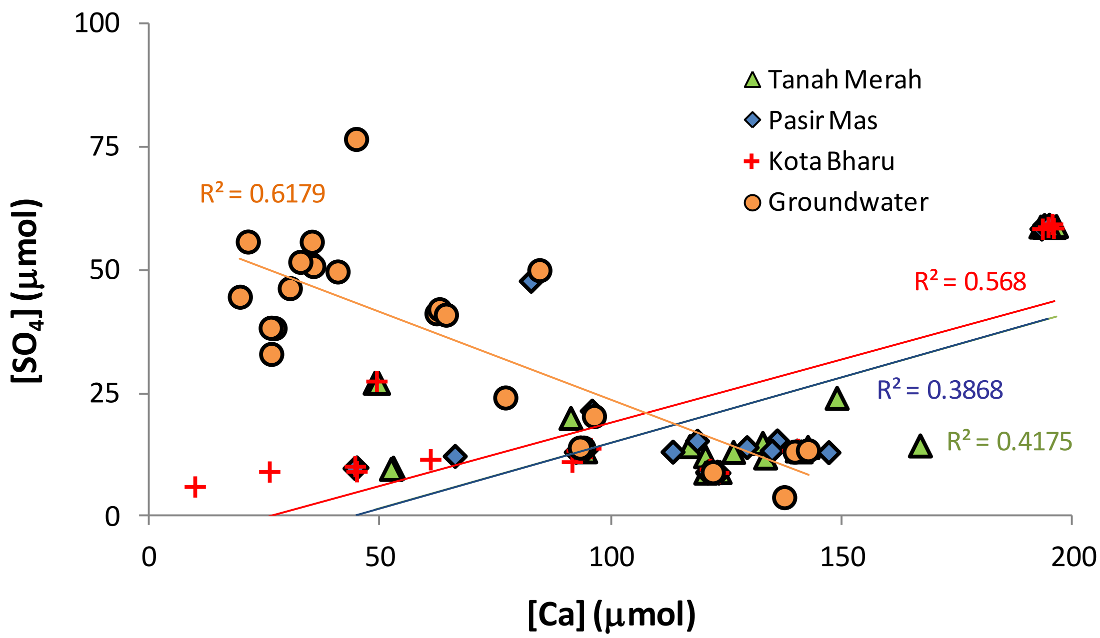


Figure 42: Plot of $[SO_4]$ vs. [Ca] for all Kelantan Basin sites.

A cross-plot of [SO_4] against [Ca] shows no discernible relationship between the two constituents (fig. 42) in the river waters, although a stronger correlation is present in groundwater. This could be due to the location of the groundwater site within a small village, where the associated aquifer is likely to be affected by pollution inputs from its surroundings. In the Kelantan River, where water quality is relatively good, most of the Ca may be geogenic in origin. There also appears to be no significant relationship between the carbon isotope/concentration data and all other variables (table 17). As with the Langat River, the PCA for carbon-related variables (table 18) yields single variable varifactors, again arguing for complex control of the aquatic carbon cycle in the river.

Table 18: PCA results for dissolved carbon in river and tributary waters, with significant loadings in bold. Source data are in appendix 4.

Parameters	Kelantan River			
	VF1	VF2	VF3	VF4
$\delta^{13}C_{DOC}$	**0.97**	-0.04	0.05	0.23
$\delta^{13}C_{DIC}$	-0.04	**0.97**	-0.22	-0.06
[DOC]	0.31	-0.07	0.36	**0.88**
[DIC]	0.05	-0.28	**0.90**	0.33
Variance Explained	26%	26%	25%	24%

In summary, the Kelantan Basin PCA results show that bedrock geology and anthropogenic influences dominate aquatic chemistry, with the latter including inputs from agricultural and industrial pollution. The varifactors pertaining to dissolved carbon and the effects of water pollution on fluvial carbon cycling will be considered in more detail in the subsequent sections.

4.2.2 Organic Carbon Dynamics

Results from the Kelantan Basin show the dominance of C3-type vegetation on riverine carbon cycling, based on the spread of $\delta^{13}C_{DOC}$ data which lies within the literature range for C3-derived carbon (fig. 43). This may reflect a continuous input of terrestrial organic carbon, with minimal superimposed biological reworking throughout the year. The turbid appearance of the river in all locations supports this notion, as the increased amount of suspended material would limit the penetration of sunlight into the water column and impede photosynthetic activity and algae production. In agreement, plots of $\delta^{13}C_{DOC}$ with [DOC] show no distinct trends, suggesting a relatively uniform source of organic carbon that changes little throughout the sampling period (fig. 44).

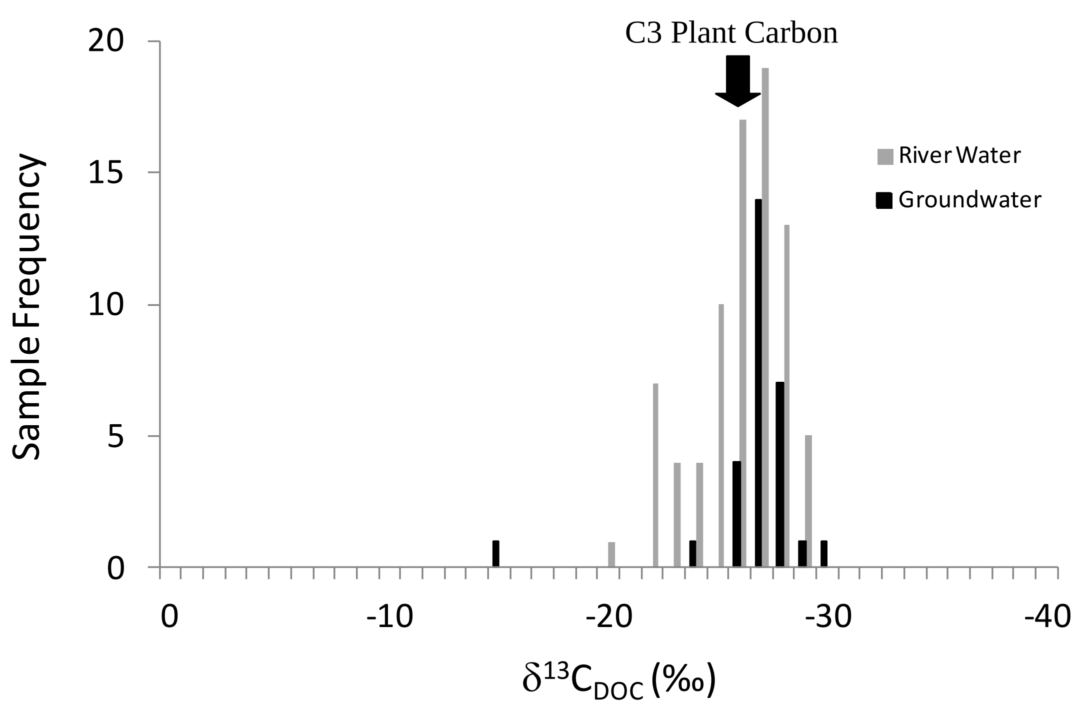


Figure 43: Histogram plot of δ^{13} C_{DOC} in the Kelantan Basin. Data from appendix 4.

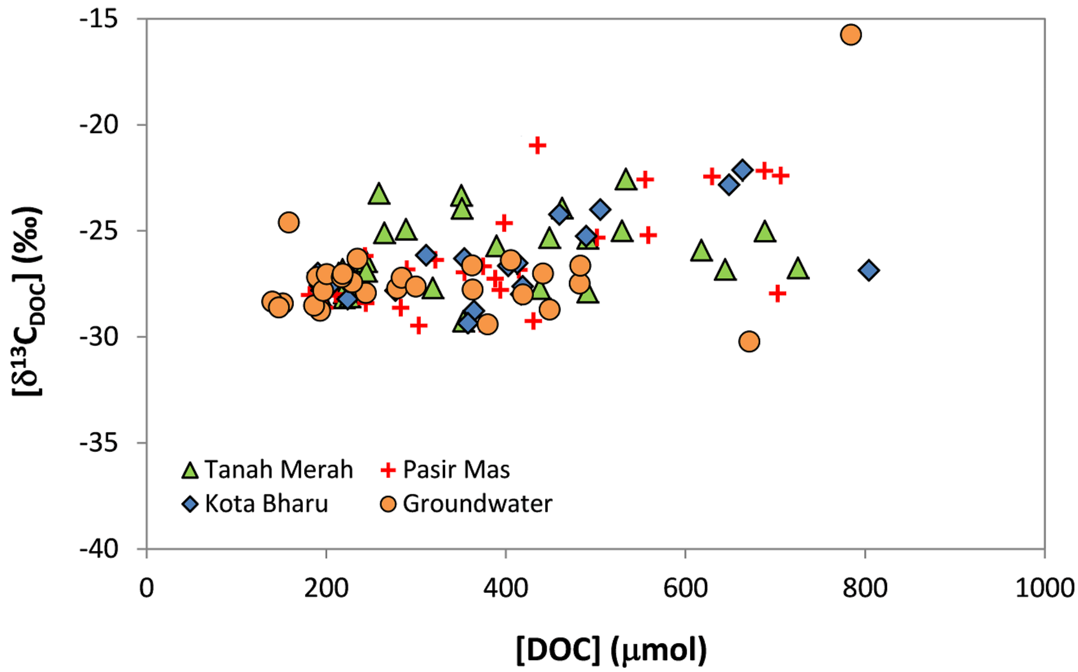


Figure 44: Plot of $\delta^{13}C_{DOC}$ vs. [DOC] for the Kelantan Basin. Solid lines bracket the general range of riverine values. Data in appendix 4.

Given the relatively low degree of urbanization, agricultural land use, and industrialization of the Kelantan Basin, anthropogenic influences on riverine organic carbon would likely be minor. While the effects of pollution should be most visible in Kota Bharu, where urban land-cover is predominant, all water quality indicators are similar to those at the site farthest up-river at Tanah Merah (table 11).

This minimal anthropogenic influence may be a function of the relatively pristine state of the watershed and the larger size of the river, rendering any pollution inputs small due to dilution. To investigate whether climatic and environmental influences on organic carbon dynamics are instead more dominant, the DOC data from Kota Bharu was compared to precipitation amounts collected from the same location. Flow data was unavailable from this site, so values from Tanah Merah were necessarily compared to data from all other locations.

The sporadic availability of the [DOC], $\delta^{13}C_{DOC}$ and flow data makes any trends difficult to clarify, but the agreement between the DOC and climatic datasets appears poor, aside from the occasional correspondence between maxima in all parameters (fig. 45). More complete sets of measurements may be needed to resolve any relationships between riverine organic carbon and climatic factors that may exist.

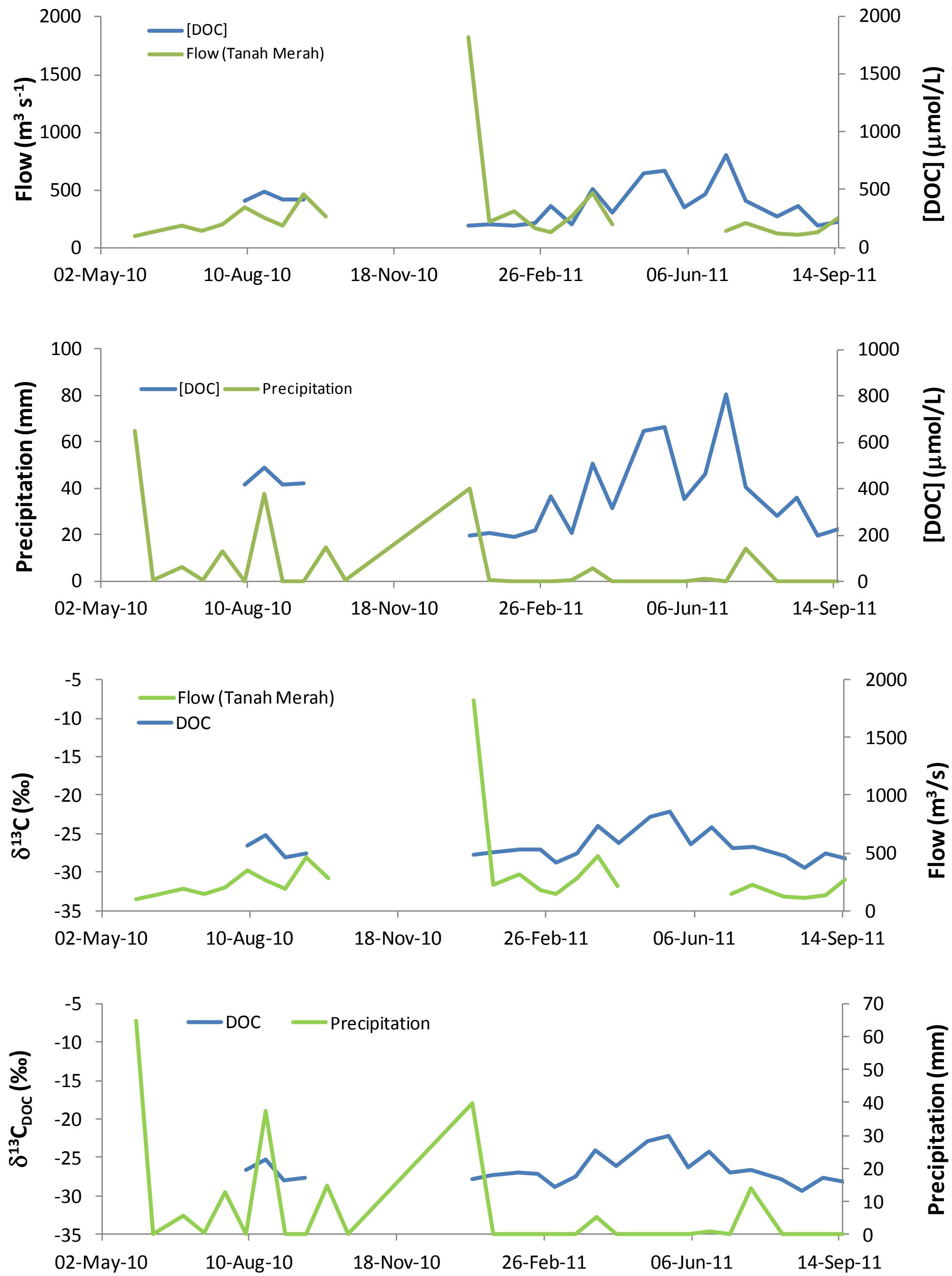


Figure 45: River flow rates from Tanah Merah and precipitation at Kota Bharu, as compared to [DOC] and $\delta^{13}C_{DOC}$ at Kota Bharu. Source data found in appendices 2 and 4.

4.2.3 Inorganic Carbon Dynamics

A general trend of decreasing $\delta^{13}C_{DIC}$ that approach C3-vegetation values as [DIC] increases, is consistent with a predominantly C3 soil-respired source of inorganic carbon (fig. 46). This ^{13}C-depletion of DIC is present in all waters but is most evident in groundwater, which also shows the highest DIC concentrations. The $\delta^{13}C_{DIC}$ groundwater values are still more ^{13}C-enriched by about 10 ‰, as compared to those expected from C3 plants. The downstream location of the groundwater site makes it more susceptible to riverine influences via inflow of river waters into the relatively shallow aquifer. The result would be a similarity between riverine and groundwater $\delta^{13}C_{DIC}$ signatures (see table 9).

The $\delta^{13}C_{DIC}$ vs. [DOC] in the river show no apparent correlation (fig. 47), again indicating that organic and inorganic carbon dynamics are not coupled. This is consistent with the PCA results, which group the DIC and DOC data into separate varifactors (table 17). As in the Langat Basin, the riverine DIC show $\delta^{13}C_{DIC}$ values that are more ^{13}C-enriched as compared to the presumed C3 plant source, but ^{13}C-depleted with respect to atmospheric CO_2 (fig. 48).

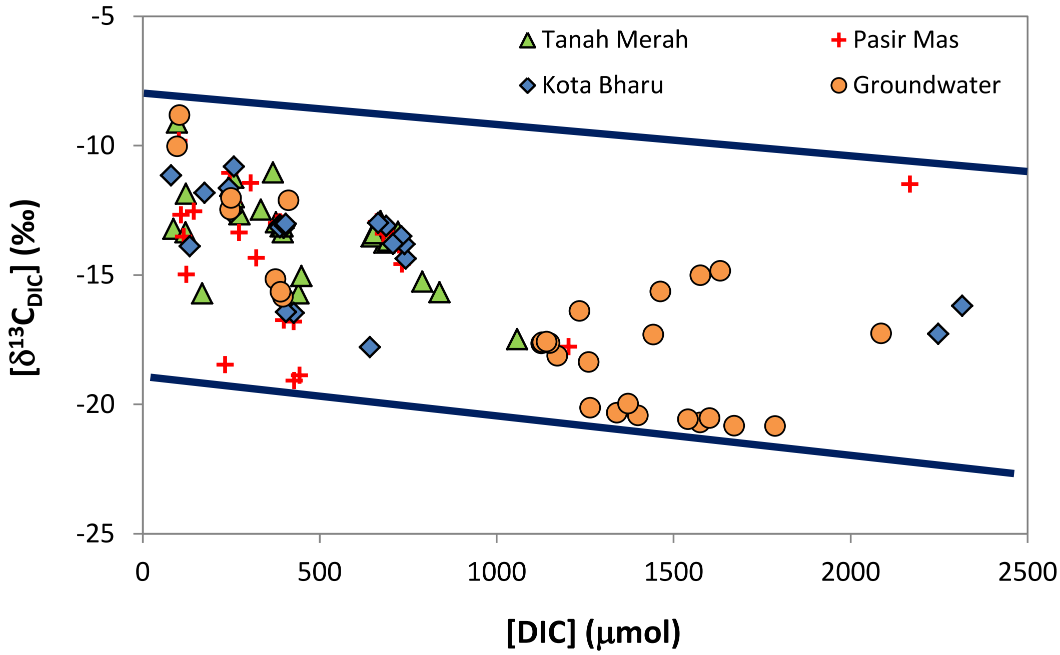


Figure 46: Plot of $\delta^{13}C_{DIC}$ vs. [DIC] for the Kelantan Basin. Solid lines bracket the general ranges of values. Data in appendix 4.

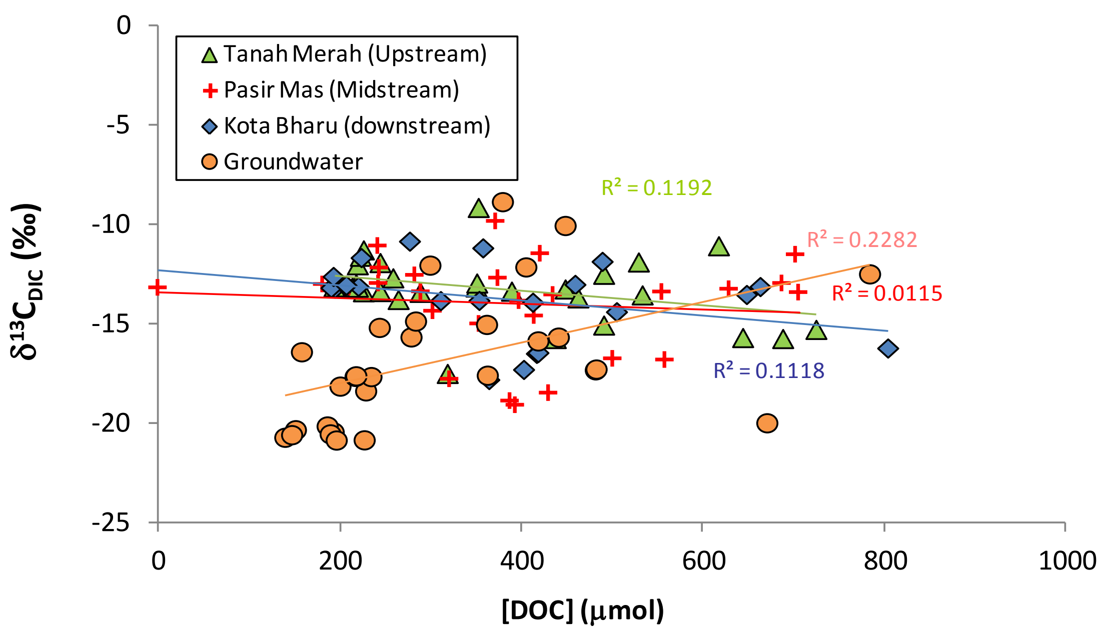


Figure 47: $\delta^{13}C_{DIC}$ versus [DOC] in the Kelantan Basin. Data in appendix 4.

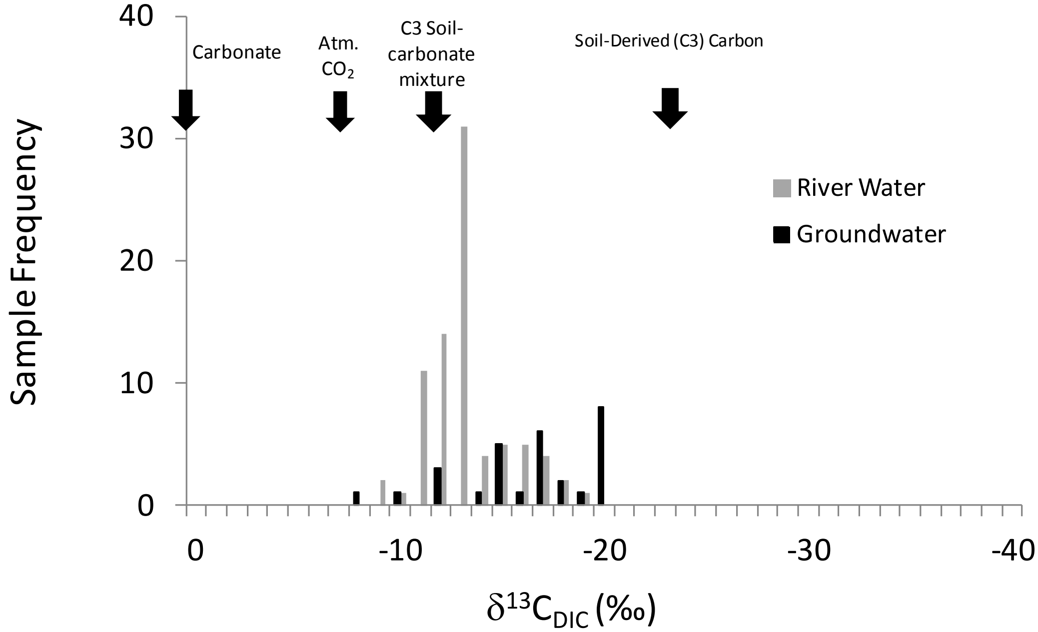


Figure 48: Histogram plot of $\delta^{13}C_{DIC}$ in the Kelantan Basin. Data for indicator arrows from Clark and Fritz (1997,) and Dubois et al. (2010). Source data in appendix 4.

Using the approach outlined in section 4.1, the possible role of atmospheric CO_2, carbonate weathering, DIC speciation, photosynthetic uptake, methanogenesis and CO_2 evasion on carbon cycling in the Kelantan River were investigated. The observed super-saturation of CO_2 in river waters suggests that CO_2 invasion is of negligible influence on riverine DIC. As with the Langat River, mixing with atmospheric CO_2 is therefore an unlikely mechanism driving the observed ^{13}C-enrichment of the DIC pool. The influence of photosynthetic activity is also probably insignificant for reasons already explained in section 4.2.1.

The plot of Mg/Na vs. Ca/Na shows that silicate weathering has the strongest influence on basin water chemistry (Fig. 49). Unlike in Langat Basin, however, no data points lie directly within the field of silicate-weathering dominance and most data appear to trend along the carbonate-evaporite axis. As with the Langat Basin, the proximity of the ocean to the sampling locations suggest that marine inputs via sea spray and aerosol deposition could explain the clustering of data towards the evaporate-dominated region of the lithology plot.

To further clarify this shift of riverine data points from the silicate domain and the possible influence of carbonate geology, the DIC contributed from the putative weathering of carbonates were calculated as in section 4.1.2. This exercise yielded averages of 42.3 %, 38.9 % and 41.5 %, in Tanah Merah, Pasir Mas, and Kota Bharu, respectively. These are similar to results from the Langat River, and are also unreasonably high estimates in view of the regional geology (table 19). Moreover, the values are lower in groundwater at 26.6 %, opposite to the expected pattern if carbonates were a major contributor to riverine DIC.

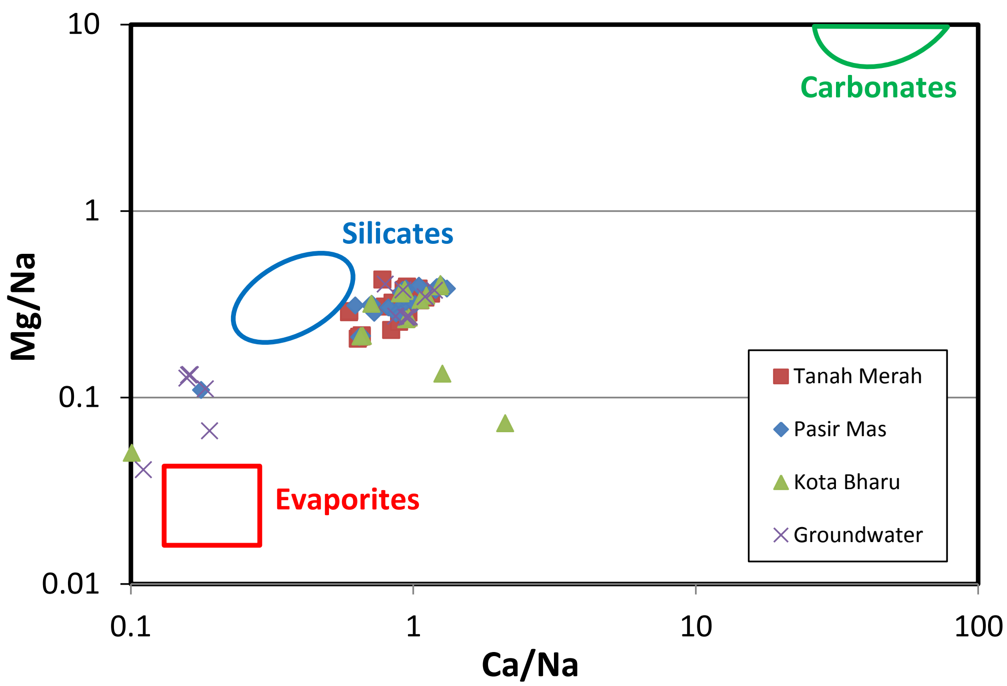


Figure 49: Plots of Mg/Na versus Ca/Na for each sampling site, using lithology fields from Gaillardet et al. (1999). Based on data in appendix 4.

Table 19: Modelled percentages of calculated theoretical carbonate inputs to riverine DIC in the Kelantan Basin.

Site	Maximum % Carbonate	Minimum % Carbonate	Average % Carbonate
Tanah Merah	60.4	24.0	42.3 ± 7.3
Pasir Mas	57.3	17.0	38.9 ± 10.2
Kota Bharu	53.0	22.7	41.5 ± 7.2
Groundwater	61.7	9.4	26.6 ± 14.6

With no CH_4 measurements made, the magnitude of methanogenic activity in the Kelantan River remains unknown. The lack of a source reservoir or lake would probably render methanogenesis a comparatively minor influence on riverine carbon as compared to the Langat Basin, unless significant methane production occurs within the river itself. But while BOD and COD can reach high levels in the Kelantan River, which could possibly induce temporary periods of anoxia within the river waters, the presence of dissolved oxygen indicate generally oxic conditions (see section 3.2.4). As methanogenesis is a strictly anoxic process, instances of methane production in the water column is improbable. Methane production in the riverbed sediments is also unlikely to be of significance, given their mobility and probable oxygenation to some depth (Richey et al., 1988).

In summary, as for the Langat River, the isotopic fractionation of riverine carbon due to DIC speciation and CO_2 evasion remains the most likely mechanism responsible for the ^{13}C-enrichment of DIC. Calculations of the hypothetical $\delta^{13}C_{HCO3}$ value prior to CO_2 evasion yields an average of -22.6 ± 2.4 ‰, nearly identical to the literature value for C3-soil carbon, confirming that the isotopic fractionation of DIC via hydration of

HCO_3^- and its subsequent evasion as CO_2 is the most likely reason for the observed dissimilarities between $\delta^{13}C_{DIC}$ and $\delta^{13}C_{org}$.

Given the similar nature of water quality indicators across all sites in the Kelantan River (see table 11) and the ostensibly low level of pollution in the basin, the significance of water pollution on DIC cycling is uncertain. However, as with DOC, anthropogenic influences on DIC cycling is minor given the more pristine nature of the Kelantan Basin. Climatic influences on DIC cycling also appear negligible, as [DIC] and $\delta^{13}C_{DIC}$ show no correlations with precipitation and river flow data during the sampling period (fig. 50), although this may also be due to the sparse nature of the data.

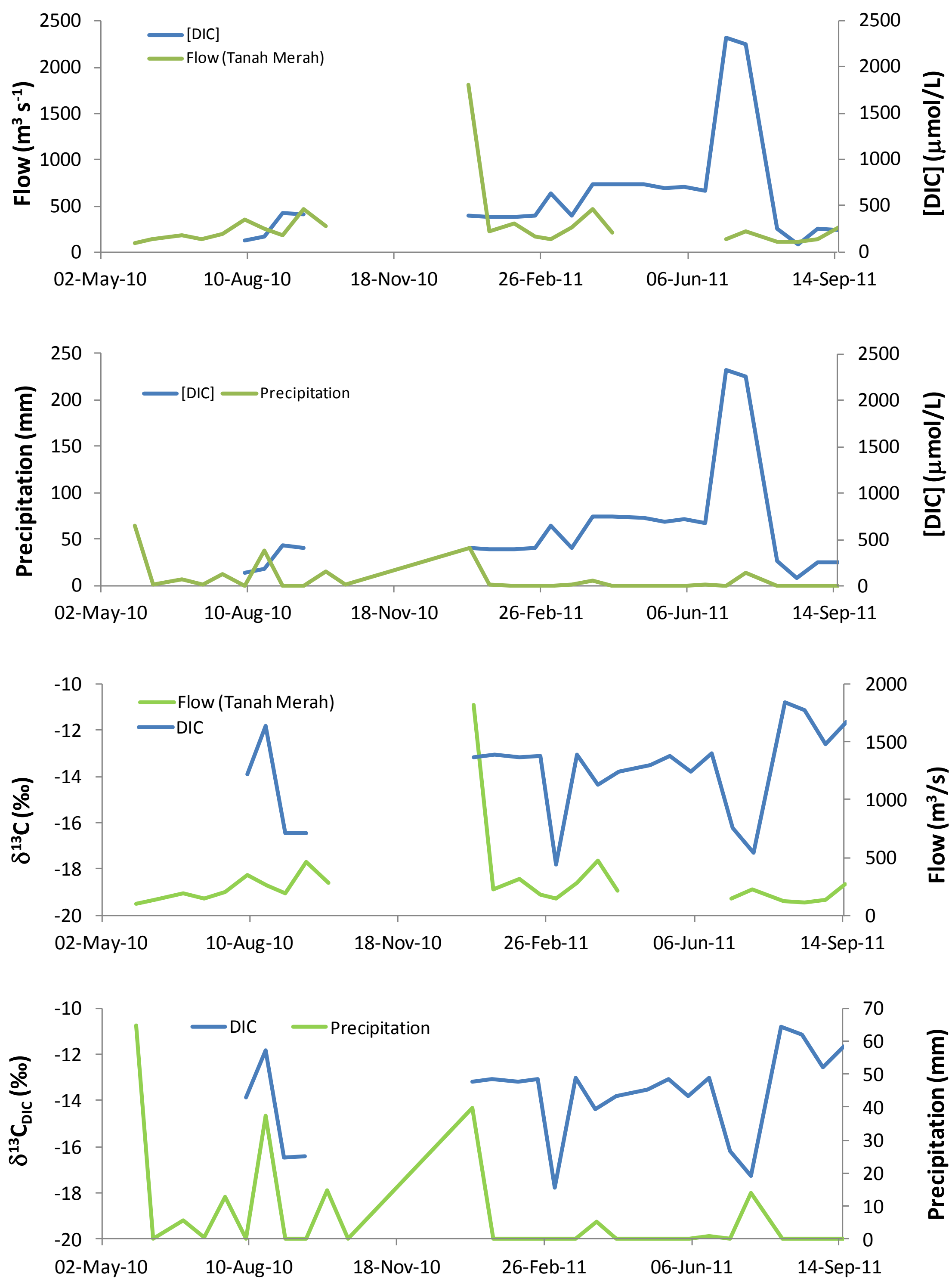


Figure 50: River flow rates and precipitation as compared to [DIC] and $\delta^{13}C_{DIC}$ in Kota Bharu. Data from appendices 2 and 4.

4.2.4 Watershed Carbon Balance

CO_2 evasion fluxes were calculated as in section 4.1.4, using equation (9) and the CO_2 values from section 3.2.3. With this method, the range of mean annual evasion rates is 1.7 kg C m^{-2} yr^{-1} to 3.5 kg C m^{-2} yr^{-1}, similar to the values calculated from the Dengkil sub-basin. Accounting for the surface area of the Kelantan River, estimated by multiplying the length of the river by its average width, the total carbon export due to CO_2 evasion ranges from 125 x 10^3 t C yr^{-1} to 260 x 10^3 t C yr^{-1} (table 20). These gas evasion rates are 1.5 to 3 times larger than the total mass of dissolved carbon exported to the ocean. This is a comparatively larger portion of the riverine carbon balance than in the Dengkil Sub-basin, likely reflecting the larger size of the Kelantan River.

The estimates of total riverine carbon export from the Kelantan basin (calculated using the methods and equations outlined in section 4.1.4) are 52.6 x 10^3 t C yr^{-1}, 31.7 x 10^3 t C yr^{-1} and 41.7 x 10^3 t C yr^{-1} for DOC, DIC and POC, respectively. Together, these estimates make a total watershed carbon export of 126 x 10^3 t C yr^{-1}. This value is comparable to the amount of carbon lost via CO_2 evasion, as based on the lower-end evasion flux estimate (table 20, fig. 51).

Table 20: Calculated carbon fluxes in the Kelantan Basin.

Carbon Fluxes	
Atmospheric flux per unit area (kg C yr^{-1} m^2): k = 1.9 m/d	1.7
Total atmospheric flux (10^3 t C yr^{-1}): k = 1.9 m/d	124.5
Atmospheric flux per unit area (kg C yr^{-1} m^2): k = 4.0 m/d	3.5
Total atmospheric flux (10^3 t C yr^{-1}): k = 4.0 m/d	259.3
Average DOC Export (10^3 t C yr^{-1})	52.6
Average DIC Export (10^3 t C yr^{-1})	31.7
Average POC export (10^3 t C yr^{-1})	41.7

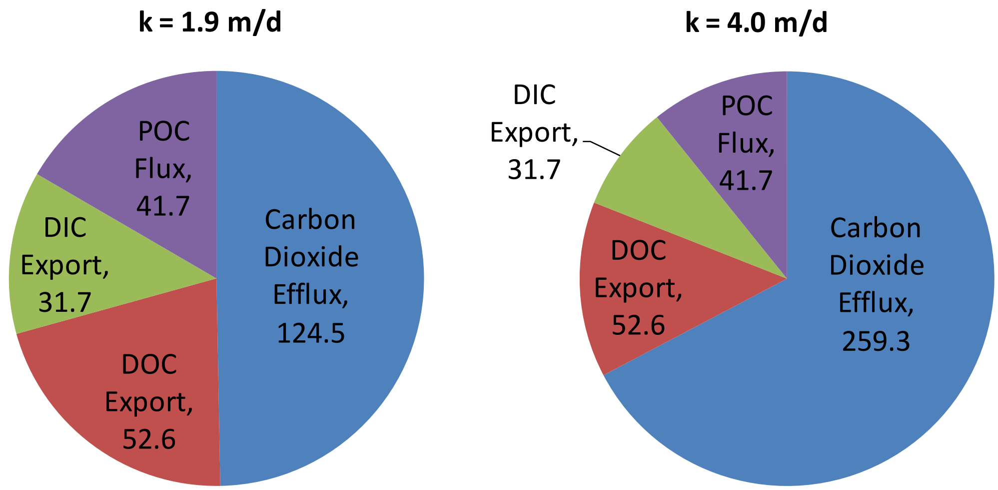


Figure 51: Summary of carbon export fluxes in the Kelantan Basin in 10^3 t C yr^{-1}, for upper and lower-end "k" estimates

Summing all of the above carbon loss estimates, the total riverine export out of the Kelantan Basin shows a range of 264 x 10^3 t C yr^{-1} to 385 x 10^3 t C yr^{-1}. A calculation of ecosystem carbon uptake, obtained from $\delta^{18}O/\delta D$ data and using methods similar to that performed on the Langat Basin dataset (Syakir, personal communication), results in a value of 18,558 x 10^3 t C yr^{-1}. Fluvial carbon losses via transport and CO_2 degassing consequently make up only 1.4 % to 2 % of sequestered carbon in the watershed.

4.3 Inter-site Differences in Riverine Carbon Cycling

Despite the considerably larger size of the Kelantan Basin and River relative to the Langat watershed, the relative percentages of carbon losses via CO_2 evasion are similar, accounting for 48 % to 65 % (Dengkil Sub-basin) and 50 % to 67% (Kelantan Basin) of the total river carbon export. The proportions of riverine DOC loss in both locations are almost identical, at 21 % of total river carbon export as based on the lower-end CO_2 evasion flux estimate. There are also similarities in the averaged [DIC], [DOC], $\delta^{13}C_{DIC}$ and $\delta^{13}C_{DOC}$ in both basins (see sections 3.1.1, 3.1.2, 3.2.1 and 3.2.2).

In summary, while the absolute values of carbon export fluxes are proportional to the basin size, the relative importance of these mechanisms of carbon loss appears to be constant. This could be due in part to the analogous geology of the two regions, as both are dominated by silicate bedrock and show a scarcity of carbonate rocks. Moreover, the climate in the Langat and Kelantan Basins is largely indistinguishable, with comparable averaged values of humidity, air temperature and precipitation. As well, both watersheds are dominated by C3-type vegetation.

There appears to be more visible differences in the proportions of total riverine carbon losses made up by POC and DIC, with a greater proportion of POC export versus DIC loss occurring in the Kelantan Basin. This may be due to the reduced urbanization and increased tree cover as compared to Langat, where land clearance and urban growth is more prevalent.

4.4 Comparisons to Riverine Carbon Cycling at Other Locations

The lower-end estimated rates of outgassing in the Langat and Kelantan Basins are in line with findings in other temperate and tropical regions dominated by silicate bedrock (fig. 52). CO_2 evasion from the Amazon Basin (Richey et al., 2002) was calculated to be 0.83 kg C m^{-2} yr^{-1}, while rates from the Mississippi River (Dubois et al., 2010) and the Nyong River in Cameroon (Brunet et al., 2009) were estimated at 1.18 kg C m^{-2} yr^{-1} and 1.49 kg C m^{-2} yr^{-1}, respectively.

In contrast, a lower value of 0.2 kg C m^{-2} yr^{-1} was calculated by Ferguson et al. (2011) using data from the Fly River, in Papua New Guinea. This comparatively low evasion rate was attributed to the carbonate geology of the Fly River Basin, which buffered CO_2 effluxes via the dissolution of carbonate minerals. This rate is similar to that observed by Telmer and Veizer (1999) in the Ottawa River (0.17 kg C m^{-2} yr^{-1}), which is located in a cold temperate region.

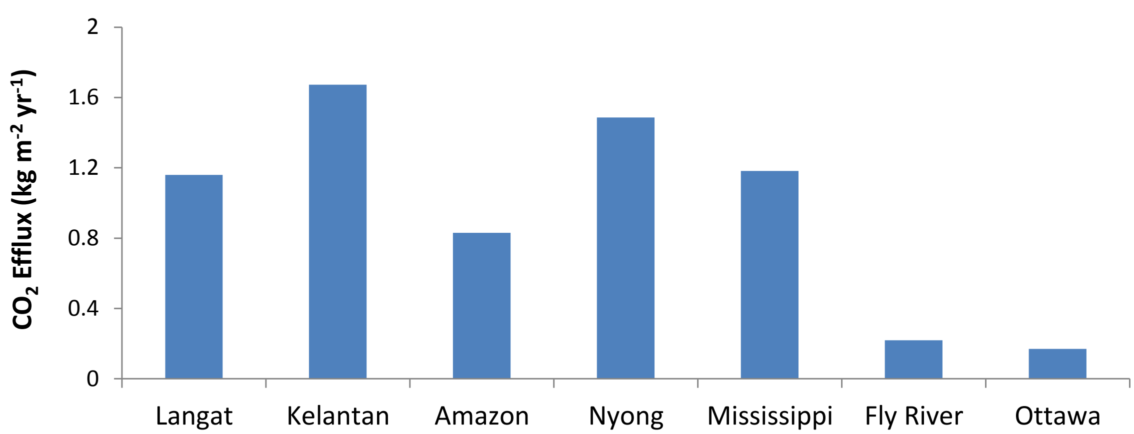


Figure 52: Comparison of Langat and Kelantan River CO_2 lower-end evasion rates with other riverine systems. See the text for sources.

As well, these same studies have also shown carbon losses via CO_2 evasion to be up to 4 times greater than that lost from DIC or DOC export (Brunet et al., 2009). By comparison, CO_2 effluxes in temperate locations account for a smaller fraction of riverine carbon loss relative to DIC or DOC export (Telmer and Veizer, 1999; Kanduč et al., 2007). The absolute magnitudes of DIC and DOC loss in temperate watersheds are also smaller than those in the tropics, due to the lower biological productivity of basins in colder climates. This is manifested in lower fluxes of carbon to the oceans and atmosphere.

Table 21: Comparisons of Langat and Kelantan Basin CO_2, DIC and DOC losses with previous research. Export is shown as percentages of combined dissolved and gaseous carbon export, due to a lack of POC data in the relevant studies.

Watershed	CO_2 Evasion (kg C m^{-2} yr^{-1})	Average $\delta^{13}C_{DIC}$ (‰)	% CO_2 Evasive Loss	% DIC Loss	% DOC Loss
Langat (k = 1.9)	1.16	-13.3 ± 2.2	52.9	24.1	23.0
Kelantan (k = 1.9)	1.67	-13.2 ± 1.4	59.6	15.2	25.2
Nyong	1.49	-12.6 ± 0.7	47.4	11.4	41.2
Amazon	0.83	-14.0 ± 1.6	86.9	6.5	6.7
Mississippi	1.18	-9.3 ± 0.3	53.7	40.1	6.2

The averaged [DIC] within the Langat and Kelantan Basins (460 ± 290 μM and 498 ± 383 μM, respectively) are within the same ranges as those in other silicate-dominated watersheds in tropical and warm temperate regions, such as in the Nyong (305 ± 99 μM) and Amazon Rivers (~780 μM). These river systems also show similar rates of CO_2 evasion, as measured per unit area of water surface (table 21).

In contrast, [DIC] is much larger in tropical watersheds underlain by carbonate bedrock, regardless of similarities in factors such as average annual precipitation, air temperature, humidity, or vegetation type. In the aforementioned study by Ferguson et al. (2011), a relatively high average [DIC] of 945 ± 127 μM was attributed to the dominance of carbonate-derived DIC inputs on river water carbon.

In a carbonate-influenced section of the Brazos River, a sub-tropical river in Texas, an even higher averaged [DIC] value of 2,800 ± 400 μM was observed, along with a comparatively low averaged pCO_2 of 760 ± 243 ppmv (Zeng et al., 2011). The lower concentrations and evasion rates of CO_2 from these carbonate-influenced rivers are indicators of the increased buffering capacities present in these systems, due to the dominance of mineralogical carbonate inputs (Ferguson et al., 2011).

5.0 Conclusions

The Langat and Kelantan Rivers are located in tropical watersheds and share similar climatic conditions, with mean annual precipitation values of over 2,000 mm and air temperatures of about $30^{o}C$. The Langat River watershed is smaller and less pristine than the Kelantan River Basin, with the bulk of the land cover comprised of agricultural and urban areas. In contrast, forests dominate the Kelantan Basin, with urbanized and cultivated land cover concentrated near the river's mouth.

PCA analyses show that the chemistry of the Langat and Kelantan Rivers are mainly influenced by geogenic and anthropogenic inputs. The geologic component shows strong loadings by elements associated with rock weathering (Ca, Mg, Mn, Si, and Sr), while loadings by another suite of chemical constituents (NO_3, SO_4, K, Zn and Cl) suggest anthropogenic inputs from industrial, urban and agricultural sources. The carbon-related data are largely decoupled from both of these factors, suggesting that alternative pollutive or natural influences have a stronger impact on the riverine carbon cycle.

Stable isotope and concentration analyses of DIC show a $\delta^{13}C_{DIC}$ signal that approaches C3-plant values at high concentrations. This trend is particularly visible in groundwater, where $\delta^{13}C_{DIC}$ values are indistinguishable from C3 plant values, suggesting that most of the DIC is sourced from the local C3 vegetation. However, while ^{13}C-depleted relative to atmospheric CO_2, most riverine $\delta^{13}C_{DIC}$ is enriched in ^{13}C relative to C3 plant signatures by ~10 ‰.

This enrichment could be due to entrainment of atmospheric CO_2 into river waters, carbonate mineral weathering, DIC speciation and loss, photosynthetic uptake, methanogenesis and fractionation via CO_2 evasion. A consistent overpressure of CO_2 within the river waters argues against atmospheric CO_2 entrainment as a plausible mechanism. The weathering of carbonate minerals is also an unlikely factor behind the observed $\delta^{13}C_{DIC}$ values, given the dearth of carbonate geology in the Langat and Kelantan Rivers.

Speciation of DIC could explain the observed enrichments, given a credible mechanism of DIC loss. Photosynthetic activity may be more prevalent in upstream reaches, but does little to explain the ^{13}C-enriched DIC in the mid- and downstream reaches of both rivers, where CO_2 overpressures are largest and primary production is limited by increased turbidity. Methanogenesis might also result in ^{13}C-enrichment of the DIC pool, but its presence in the Langat and Kelantan Rivers is hypothetical in the absence of direct CH_4 measurements.

Considering all of the above, the most probable mechanism for ^{13}C-enrichment of riverine DIC is CO_2 evasion across the water surface, following the hydration of riverine HCO_3^-. The CO_2 overpressures in the river water would result in gas diffusion into the atmosphere, leading to a progressive ^{13}C-enrichment of the residual DIC pool. This conclusion is supported by calculations of the hypothetical $\delta^{13}C$ of respired carbon based on the DIC dataset, which show values similar to that of soil-respired carbon.

The $\delta^{13}C_{DOC}$ data uniformly show values within the C3-plant range during the entire sampling period in all locations, consistent with the dominance of this plant type within the Langat and Kelantan Basins. Occasionally, large ^{13}C-depletions during some sampling periods do exist, indicating enhanced *in-situ* primary production. In the Langat River, these features are more significant in the upstream locations. Previous studies have established the prevalence of algae growth at these sites, and the reduced turbidity and pollution may also facilitate photosynthetic activity within the upstream area.

The larger concentrations of DIC and DOC, as well as all water quality parameters, in the mid- and downstream locations of the Langat River are likely due to enhanced anthropogenic pollution in that section of the watershed. This is probably mainly associated with inputs from domestic sewage and POME discharge. In these instances, the anthropogenic stable carbon isotope signature is indistinguishable from natural signals, given the ultimately biological origin of carbon from all the above sources.

Estimates of carbon fluxes show significant losses of carbon via CO_2 outgassing, which accounts for about 40 % to 67 % of the total export in both watersheds. This proportion is comparable to, or larger than the combined outflow of DIC and DOC in either basin, and is similar to the total fluvial export of dissolved and particulate carbon. Analogous proportions of evasive CO_2 loss have been observed in previous studies within tropical environments, with colder, temperate locations showing lower CO_2 evasion rates due to reduced biological activity and rates of mineral weathering.

Therefore, CO_2 evasion from water surfaces is a significant mechanism of carbon loss, confirming previous studies in tropical locations that shown gas evasive losses to be considerable. However, the sum of all carbon losses via fluvial transport and gas evasion is only a small fraction of the total amount of carbon sequestered by the watershed ecosystems: about 3 % or less in both the Langat and Kelantan Basins. Similar proportions of carbon loss and stable isotope characteristics are shared by the two watersheds, suggesting that basin size, and agricultural and urban land-use are minor influences on riverine carbon cycling.

This research provides a reconnaissance study of two watersheds in Southeast Asia, a region from which data is sparse with regards to stable isotope systematics of riverine carbon cycling. The findings confirm the complexity of carbon cycling in fluvial systems within this tropical region, where carbon species are not merely transported to the ocean but are subject to processes of consumption, production and modification *in-situ*. As well, this is one of few studies that have investigated the effects of urban and agricultural development, in addition to watershed scale, on the tropical riverine carbon cycle. The results of this inquiry has revealed that factors such as the plant type of the surrounding vegetation and underlying geology may be the dominant influences on carbon cycling in these environments.

6.0 References

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APPENDICES

Appendix 1: Physico-chemical data from the Dengkil sub-basin, measured in-situ

Date	*Location*	*Water Temperature (^oC)*	*pH*	*EC (μS)*	*TDS (ppm)*
16-May-10	Pangsun	30.0	N/A	122.00	61.00
	Kajang	28.1	6.88	496.00	265.00
	Dengkil	29.0	N/A	997.00	524.00
	Semenyih	29.3	N/A	590.00	295.00
	Groundwater	N/A	7.00	110.00	50.00
30-May-10	Pangsun	N/A	N/A	N/A	N/A
	Kajang	N/A	N/A	N/A	N/A
	Dengkil	N/A	N/A	N/A	N/A
	Semenyih	N/A	N/A	N/A	N/A
	Groundwater	N/A	N/A	N/A	N/A
15-Jun-10	Pangsun	N/A	N/A	N/A	N/A
	Kajang	N/A	N/A	N/A	N/A
	Dengkil	N/A	N/A	N/A	N/A
	Semenyih	N/A	N/A	N/A	N/A
	Groundwater	N/A	N/A	N/A	N/A
29-Jun-10	Pangsun	N/A	N/A	N/A	N/A
	Kajang	N/A	N/A	N/A	N/A
	Dengkil	N/A	N/A	N/A	N/A
	Semenyih	N/A	N/A	N/A	N/A
	Groundwater	N/A	N/A	N/A	N/A
11-Jul-10	Pangsun	N/A	N/A	N/A	N/A
	Kajang	N/A	N/A	N/A	N/A
	Dengkil	N/A	N/A	N/A	N/A
	Semenyih	N/A	N/A	N/A	N/A
	Groundwater	N/A	N/A	N/A	N/A
25-Jul-10	Pangsun	N/A	7.12	N/A	N/A
	Kajang	N/A	7.13	N/A	N/A
	Dengkil	N/A	7.32	N/A	N/A
	Semenyih	N/A	N/A	N/A	N/A
	Groundwater	N/A	6.00	N/A	N/A
07-Aug-10	Pangsun	26.1	6.79	1008	365
	Kajang	27.3	6.87	357	142
	Dengkil	28.8	6.41	579	121
	Semenyih	28.5	6.54	271	103
	Groundwater	25.2	5.87	489	270
21-Aug-10	Pangsun	26.5	7.06	1019	459
	Kajang	27.0	6.79	346	173
	Dengkil	27.6	6.77	820	192
	Semenyih	27.3	6.67	437	373
	Groundwater	25.2	5.76	640	290

Date	Location	Water Temperature (^{o}C)	pH	EC (μS)	TDS (ppm)
07-Sep-10	Pangsun	26.7	6.37	1050	581
	Kajang	27.1	6.71	791	237
	Dengkil	28.9	6.63	927	361
	Semenyih	27.8	6.51	793	289
	Groundwater	25.5	5.89	218	573
25-Sep-10	Pangsun	27.7	6.27	1279	660
	Kajang	27.2	6.66	1158	413
	Dengkil	28.7	6.39	1226	496
	Semenyih	27.9	6.42	1031	279
	Groundwater	25.7	5.93	370	661
17-Oct-10	Pangsun	27.8	6.29	1093	384
	Kajang	29.7	6.83	1109	498
	Dengkil	28.5	6.57	569	194
	Semenyih	28.9	6.87	619	217
	Groundwater	27.8	5.92	597	237
31-Oct-10	Pangsun	28.3	7.43	1288	593
	Kajang	30.0	7.00	2412	798
	Dengkil	28.6	7.24	453	183
	Semenyih	28.7	7.51	601	283
	Groundwater	29.0	5.97	698	698
15-Nov-10	Pangsun	27.9	6.03	1747	779
	Kajang	28.5	6.59	946	803
	Dengkil	29.2	6.35	662	585
	Semenyih	29.0	6.68	495	253
	Groundwater	27.5	5.46	940	337
30-Nov-10	Pangsun	27.1	6.19	1142	693
	Kajang	27.5	6.48	1224	678
	Dengkil	29.4	6.31	501	481
	Semenyih	28.7	6.53	319	278
	Groundwater	26.1	5.56	813	527
5-Dec-10	Pangsun	26.3	6.89	761	658
	Kajang	28.7	7.07	907	356
	Dengkil	28.0	7.23	459	347
	Semenyih	28.3	7.10	578	598
	Groundwater	26.0	5.91	689	553
19-Dec-10	Pangsun	26.8	6.97	761	345
	Kajang	27.5	6.93	1903	761
	Dengkil	29.6	7.13	478	389
	Semenyih	28.7	7.10	756	546
	Groundwater	26.1	6.01	546	681
9-Jan-11	Pangsun	26.2	7.30	609	587
	Kajang	27.0	7.24	897	304
	Dengkil	28.9	7.13	1391	105
	Semenyih	27.5	7.10	1083	566
	Groundwater	25.8	6.52	542	289

Date	*Location*	*Water Temperature (^oC)*	*pH*	*EC (μS)*	*TDS (ppm)*
22-Jan-11	Pangsun	26.5	6.26	542	653
	Kajang	28.1	7.36	897	479
	Dengkil	29.1	7.31	561	783
	Semenyih	28.5	7.17	735	517
	Groundwater	26.1	6.19	667	305
12-Feb-11	Pangsun	25.9	7.23	421	207
	Kajang	26.0	7.15	659	361
	Dengkil	27.3	7.23	434	437
	Semenyih	27.3	7.10	751	291
	Groundwater	25.3	6.19	308	451
26-Feb-11	Pangsun	26.0	6.89	693	543
	Kajang	26.3	6.97	887	600
	Dengkil	28.1	6.43	677	221
	Semenyih	27.8	6.58	317	516
	Groundwater	25.8	6.01	488	139
13-Mar-11	Pangsun	26.0	7.33	937	291
	Kajang	26.1	7.01	1126	247
	Dengkil	27.8	7.23	541	213
	Semenyih	27.1	7.34	845	253
	Groundwater	25.3	5.98	481	316
27-Mar-11	Pangsun	26.1	7.89	685	671
	Kajang	26.8	7.00	761	568
	Dengkil	27.2	7.63	433	233
	Semenyih	27.0	7.91	702	439
	Groundwater	25.8	6.00	351	311
10-Apr-11	Pangsun	27.0	7.56	307	343
	Kajang	27.5	7.05	528	527
	Dengkil	28.0	6.17	107	348
	Semenyih	27.9	6.31	145	473
	Groundwater	25.0	7.01	55	234
24-Apr-11	Pangsun	27.4	6.39	1142	468
	Kajang	28.0	6.78	1224	574
	Dengkil	29.8	6.77	501	412
	Semenyih	28.7	6.14	319	709
	Groundwater	29.0	6.41	813	322
7-May-11	Pangsun	27.2	6.67	631	256
	Kajang	27.5	6.52	704	381
	Dengkil	28.9	7.03	426	493
	Semenyih	29.6	6.73	522	512
	Groundwater	28.3	7.11	744	370
21-May-11	Pangsun	26.0	7.09	815	706
	Kajang	26.8	7.02	794	589
	Dengkil	28.8	6.54	309	756
	Semenyih	29.0	6.79	417	551
	Groundwater	27.8	7.12	663	891

Date	Location	Water Temperature (^{o}C)	pH	EC (μS)	TDS (ppm)
12-Jun-11	Pangsun	27.0	6.61	715	360
	Kajang	26.4	6.81	1498	552
	Dengkil	28.3	6.27	417	164
	Semenyih	29.8	6.15	515	276
	Groundwater	27.3	6.34	578	543
26-Jun-11	Pangsun	27.1	6.31	709	289
	Kajang	26.7	6.96	1481	512
	Dengkil	28.5	6.27	437	161
	Semenyih	30.5	6.15	518	269
	Groundwater	27.9	6.14	563	539
16-Jul-11	Pangsun	26.1	6.12	591	515
	Kajang	25.9	6.31	813	466
	Dengkil	27.8	6.35	587	419
	Semenyih	27.3	6.19	592	563
	Groundwater	25.0	6.01	638	786
30-Jul-11	Pangsun	26.5	7.08	200	69
	Kajang	25.8	7.22	1064	319
	Dengkil	26.7	6.62	143	69
	Semenyih	26.3	6.59	171	73
	Groundwater	23.8	6.66	55	80
18-Aug-11	Pangsun	26.5	6.83	421	557
	Kajang	26.8	6.99	518	409
	Dengkil	29.0	7.03	419	405
	Semenyih	28.8	6.99	521	319
	Groundwater	26.0	6.81	319	433
26-Aug-11	Pangsun	26.0	6.97	568	603
	Kajang	26.5	7.01	671	451
	Dengkil	28.3	7.27	415	503
	Semenyih	27.8	7.40	711	418
	Groundwater	25.3	6.53	315	314
13-Sep-11	Pangsun	26.0	7.00	633	444
	Kajang	26.3	7.05	819	310
	Dengkil	27.3	7.21	659	577
	Semenyih	27.3	7.13	911	608
	Groundwater	25.0	6.31	391	359
30-Sep-11	Pangsun	26.0	6.89	635	618
	Kajang	26.3	7.02	891	567
	Dengkil	28.8	7.21	819	516
	Semenyih	28.9	7.11	940	495
	Groundwater	25.8	6.31	581	439
16-Oct-11	Pangsun	26.8	6.81	471	515
	Kajang	27.0	6.99	555	387
	Dengkil	26.5	7.00	373	549
	Semenyih	26.5	6.95	678	711
	Groundwater	25.8	6.19	396	451

Date	***Location***	***Water Temperature (^oC)***	***pH***	***EC (μS)***	***TDS (ppm)***
29-Oct-11	Pangsun	25.7	6.70	619	258
	Kajang	28.1	6.60	401	150
	Dengkil	31.3	6.67	253	111
	Semenyih	30.7	6.78	307	501
	Groundwater	26.5	6.73	351	196
12-Nov-11	Pangsun	26.3	6.53	309	601
	Kajang	27.9	6.59	435	281
	Dengkil	28.5	6.75	330	315
	Semenyih	28.3	6.90	349	283
	Groundwater	25.8	6.31	511	305
26-Nov-11	Pangsun	25.5	6.79	489	459
	Kajang	26.5	6.51	325	220
	Dengkil	28.9	6.83	355	547
	Semenyih	28.0	6.77	300	324
	Groundwater	25.0	6.37	568	355
17-Dec-11	Pangsun	24.5	6.39	568	566
	Kajang	27.1	6.72	446	356
	Dengkil	29.0	6.81	300	367
	Semenyih	28.0	6.17	205	351
	Groundwater	23.7	6.55	349	417
31-Dec-11	Pangsun	26.5	6.70	26	287
	Kajang	27.4	6.61	231	115
	Dengkil	31.1	6.67	212	111
	Semenyih	30.7	6.79	102	451
	Groundwater	25.4	6.83	489	169

Appendix 2: Physico-chemical data from the Kelantan Basin, measured in-situ

Date	***Location***	***Water Temperature (^{o}C)***	***pH***
25-May-10	Tanah Merah	N/A	7.8
	Pasir Mas	N/A	7.3
	Kota Bharu	N/A	N/A
	Groundwater	N/A	N/A
12-Jun-10	Tanah Merah	30.1	7.8
	Pasir Mas	32.2	8.2
	Kota Bharu	N/A	N/A
	Groundwater	28.7	6.5
26-Jun-10	Tanah Merah	28.4	8.2
	Pasir Mas	29.3	8.5
	Kota Bharu	N/A	N/A
	Groundwater	30.4	6.9
10-Jul-10	Tanah Merah	29.4	9.0
	Pasir Mas	30.6	9.1
	Kota Bharu	N/A	N/A
	Groundwater	27.8	7.9
24-Jul-10	Tanah Merah	28.8	9.0
	Pasir Mas	28.4	9.0
	Kota Bharu	N/A	N/A
	Groundwater	29.7	9.1
8-Aug-10	Tanah Merah	27.9	9.0
	Pasir Mas	28.6	8.5
	Kota Bharu	26.9	8.9
	Groundwater	30.3	8.6
21-Aug-10	Tanah Merah	28.2	8.2
	Pasir Mas	29.1	8.9
	Kota Bharu	27.0	8.9
	Groundwater	29.1	8.2

Appendix 3: Geochemical data from the Langat River (carbon data measured at the G.G. Hatch Laboratory, cation data measured via ICP-AES, anion data measured via ion chromatograph).

Date	Location	[DIC] (μM)	[DOC] (μM)	$\delta^{13}C$ DIC (‰)	$\delta^{13}C$ DOC (‰)	Ca (μM)	Fe (μM)	K (μM)	Mg (μM)	Mn (μM)	Na (μM)	Zn (μM)	Cl- (μM)	Si (μM)	SO_4 (μM)	Sr (μM)	NO_3 (μM)
16-May-10	Pangsun	280	149	-7.2	-29.1	69	50.1	59	36	2.5	99	0.01	23	N/A	5	0.2	N/A
	Kajang	989	265	-14.5	-25.4	415	0.8	130	50	0.7	575	0.15	337	N/A	160	0.3	N/A
	Dengkil	515	283	-13.1	-25.0	266	0.7	112	42	0.4	335	0.04	215	N/A	115	0.3	N/A
	Semenyih	313	331	-12.7	-24.6	138	1.6	237	31	1.7	229	0.14	N/A	N/A	N/A	0.2	N/A
	Groundwater	348	88	-21.8	-29.5	16	0.7	28	8	0.4	65	0.76	N/A	N/A	N/A	0.1	N/A
30-May-10	Pangsun	179	155	-10.0	-28.6	56	0.4	56	32	0.0	102	0.06	N/A	N/A	N/A	0.1	N/A
	Kajang	357	269	-13.4	-25.0	241	0.8	74	24	0.0	252	0.19	N/A	N/A	N/A	0.2	N/A
	Dengkil	191	366	-13.9	-23.9	169	0.9	78	22	0.0	164	0.10	N/A	N/A	N/A	0.2	N/A
	Semenyih	237	282	-13.9	-24.8	133	2.8	103	27	0.0	224	0.11	N/A	N/A	N/A	0.2	N/A
	Groundwater	205	122	-21.9	-28.9	16	0.3	29	8	0.4	66	0.82	N/A	N/A	N/A	0.0	N/A
15-Jun-10	Pangsun	1318	249	-13.8	-27.2	57	12.5	56	36	0.3	98	0.03	N/A	N/A	N/A	0.1	N/A
	Kajang	337	560	-11.8	-26.7	398	8.5	131	50	4.6	620	0.26	N/A	N/A	N/A	0.3	N/A
	Dengkil	913	522	-13.4	-25.3	299	2.4	109	48	0.0	396	0.19	N/A	N/A	N/A	0.3	N/A
	Semenyih	468	702	-14.4	-25.7	138	4.8	98	30	1.5	288	0.31	N/A	N/A	N/A	0.2	N/A
	Groundwater	453	163	-23.0	-29.6	16	0.2	27	9	0.4	63	1.11	N/A	N/A	N/A	0.1	N/A
29-Jun-10	Pangsun	271	263	-8.7	-29.0	48	0.9	56	34	0.2	100	0.23	N/A	N/A	N/A	0.1	N/A
	Kajang	387	630	-12.6	-22.9	247	0.7	68	22	2.0	180	0.23	N/A	N/A	N/A	0.2	N/A
	Dengkil	497	418	-12.0	-26.5	212	1.9	93	32	1.1	275	0.21	N/A	N/A	N/A	0.2	N/A
	Semenyih	354	404	-11.4	-25.5	122	4.5	96	27	0.8	244	0.20	N/A	N/A	N/A	0.2	N/A
	Groundwater	398	193	-21.7	-27.4	22	0.1	30	10	0.4	76	0.64	N/A	N/A	N/A	0.1	N/A
11-Jul-10	Pangsun	262	293	-7.6	-29.1	49	0.4	56	35	0.1	102	0.19	N/A	N/A	N/A	0.1	N/A
	Kajang	860	603	-13.2	-23.6	294	1.1	94	38	1.7	359	1.23	N/A	N/A	N/A	0.2	N/A
	Dengkil	535	478	-12.3	-25.0	216	3.1	98	35	0.2	303	0.05	N/A	N/A	N/A	0.2	N/A
	Semenyih	420	431	-13.1	-26.7	127	4.1	95	29	0.9	223	0.13	N/A	N/A	N/A	0.2	N/A
	Groundwater	459	162	-22.5	-29.4	19	0.0	30	9	0.4	70	0.55	N/A	N/A	N/A	0.1	N/A
25-Jul-10	Pangsun	282	234	-10.1	-28.8	53	0.9	56	35	0.0	104	0.09	N/A	N/A	N/A	0.1	N/A
	Kajang	1326	438	-14.6	-27.1	404	1.1	119	48	0.0	580	0.15	N/A	N/A	N/A	0.3	N/A
	Dengkil	938	352	-12.7	-26.8	322	1.2	123	51	0.2	500	0.06	N/A	N/A	N/A	0.3	N/A
	Semenyih	443	417	-14.4	-26.1	142	2.6	101	33	0.1	262	0.23	N/A	N/A	N/A	0.2	N/A
	Groundwater	534	172	-22.6	-29.4	17	0.1	27	9	0.4	69	1.23	N/A	N/A	N/A	0.1	N/A
07-Aug-10	Pangsun	65	316	-11.0	-29.2	54	0.4	178	33	0.0	157	0.10	186	N/A	10	0.1	N/A
	Kajang	221	343	-13.6	-27.7	295	1.2	111	38	0.0	382	0.22	230	N/A	129	0.3	N/A
	Dengkil	173	390	-12.0	-26.7	265	0.1	195	42	0.0	398	0.03	343	N/A	126	0.2	N/A
	Semenyih	103	445	-13.2	-25.8	144	1.2	111	33	0.0	319	0.17	188	N/A	78	0.2	N/A
	Groundwater	57	288	-17.1	-29.2	21	0.0	135	8	0.4	73	0.65	147	N/A	9	0.1	N/A
21-Aug-10	Pangsun	88	353	-9.7	-28.3	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.0	N/A
	Kajang	190	555	-13.8	-25.2	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.0	N/A
	Dengkil	137	582	-14.0	-23.3	209	1.8	265	36	0.9	241	0.24	348	N/A	93	0.2	N/A
	Semenyih	113	549	-13.2	-25.8	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.0	N/A
	Groundwater	143	760	-22.0	-25.8	23	N/A	112	8	0.4	72	1.94	52	N/A	9	0.1	N/A
07-Sep-10	Pangsun	81	199	-14.2	-28.8	47	0.8	444	29	0.2	84	0.39	460	N/A	8	0.1	N/A
	Kajang	168	334	-14.4	-25.7	239	0.9	489	33	0.4	199	0.14	568	N/A	86	0.2	N/A
	Dengkil	124	323	-13.7	-25.7	182	1.2	183	32	0.4	163	0.16	230	N/A	76	0.2	N/A
	Semenyih	177	439	-14.4	-24.8	162	2.6	143	31	0.5	509	0.18	237	N/A	172	0.3	N/A
	Groundwater	136	147	-21.4	-29.6	19	0.2	29	9	0.4	69	0.60	34	N/A	8	0.1	N/A
25-Sep-10	Pangsun	84	234	-10.6	-27.4	56	0.4	536	33	0.1	87	0.32	557	N/A	8	0.1	N/A
	Kajang	210	482	-14.2	-25.3	280	1.2	484	34	1.3	231	0.36	576	N/A	103	0.2	N/A
	Dengkil	134	293	-14.4	-27.0	206	1.7	78	31	0.8	202	0.18	135	N/A	100	0.2	N/A
	Semenyih	228	352	-14.7	-25.5	186	1.8	112	31	0.5	576	0.31	218	N/A	193	0.3	N/A
	Groundwater	121	225	-22.1	-27.8	24	0.4	41	9	0.4	72	0.85	45	N/A	9	0.1	N/A
17-Oct-10	Pangsun	269	251	-9.4	-28.5	35	0.5	36	17	0.0	56	0.32	93	101	13	0.1	18
	Kajang	1259	425	-13.8	-26.2	158	0.1	550	18	0.8	178	0.34	1228	117	112	0.1	9
	Dengkil	265	406	-10.4	-26.8	65	0.1	375	16	0.0	94	0.18	827	105	53	0.1	41
	Semenyih	482	385	-11.7	-26.1	99	0.1	194	16	0.0	128	0.11	540	100	83	0.1	94
	Groundwater	448	323	-11.6	-27.8	8	0.0	15	3	0.1	33	0.19	40	106	8	0.0	N/A
31-Oct-10	Pangsun	264	224	-9.4	-28.5	29	0.2	33	17	0.0	48	0.16	80	99	9	0.1	N/A
	Kajang	1666	395	-14.4	-26.5	156	0.1	551	17	0.6	178	0.33	1285	115	115	0.1	9
	Dengkil	337	243	-11.6	-27.8	72	0.2	486	15	0.0	107	0.16	1061	106	66	0.1	51
	Semenyih	488	346	-12.0	-27.1	105	0.1	207	18	0.0	133	0.08	512	99	85	0.1	88
	Groundwater	548	194	-11.7	-29.4	N/A	N/A	N/A	N/A	0.0	N/A	0.00	28	0	8	0.0	N/A
15-Nov-10	Pangsun	251	200	-9.8	-28.8	12	0.4	16	10	0.0	22	0.06	36	51	8	0.0	4
	Kajang	528	145	-13.0	-25.8	117	1.4	256	16	0.2	153	0.48	649	115	85	0.1	58
	Dengkil	489	719	-12.6	-18.0	96	2.4	40	15	0.2	107	0.23	162	78	81	0.1	48
	Semenyih	386	402	-12.7	-27.0	67	0.5	76	14	0.3	96	0.28	208	92	61	0.1	34
	Groundwater	1113	213	-22.8	-29.0	13	0.4	257	5	0.3	36	1.11	588	104	9	0.0	N/A

Date	Location	[DIC] (μM)	[DOC] (μM)	$\delta^{13}C$ DIC (‰)	$\delta^{13}C$ DOC (‰)	Ca (μM)	Fe (μM)	K (μM)	Mg (μM)	Mn (μM)	Na (μM)	Zn (μM)	Cl- (μM)	Si (μM)	SO_4 (μM)	Sr (μM)	NO_3 (μM)
30-Nov-10	Pangsun	225	162	-11.1	-27.9	N/A	N/A	0	N/A	0.0	N/A	0.00	40	0	9	0.0	N/A
	Kajang	532	132	-13.2	-25.7	106	0.4	237	16	0.2	132	0.24	570	111	76	0.1	43
	Dengkil	233	264	-9.2	-25.1	86	0.5	54	15	0.2	132	0.66	186	83	86	0.1	41
	Semenyih	303	123	-14.3	-26.8	70	0.9	44	13	0.3	115	0.40	138	88	75	0.1	40
	Groundwater	453	3	-21.9	-25.5	11	0.1	260	5	0.2	38	0.12	575	100	9	0.0	N/A
5-Dec-10	Pangsun	247	93	-15.8	-27.0	25	0.1	33	16	0.0	46	0.41	42	97	10	0.1	N/A
	Kajang	404	235	-12.6	-25.2	104	0.0	216	15	0.0	126	0.23	182	110	34	0.1	4
	Dengkil	254	155	-11.6	-26.3	89	1.4	52	15	0.0	101	0.62	185	80	76	0.1	97
	Semenyih	239	228	-13.8	-25.6	63	0.2	59	13	0.0	85	0.15	169	86	60	0.1	N/A
	Groundwater	134	27	-11.0	-23.8	10	0.1	259	5	0.1	38	0.36	578	100	9	0.0	N/A
19-Dec-10	Pangsun	291	96	-12.6	-32.0	30	1.1	26	17	0.0	48	0.01	21	113	7	0.1	8
	Kajang	634	178	-14.0	-26.1	208	0.3	60	23	0.5	226	1.16	271	107	707	0.2	64
	Dengkil	698	327	-12.3	-23.1	144	0.6	49	21	0.1	188	1.09	236	97	127	0.1	72
	Semenyih	391	211	-11.7	-27.0	74	0.3	344	15	0.1	126	0.09	797	111	75	0.1	61
	Groundwater	416	25	-22.0	-28.7	8	0.0	13	4	0.2	31	0.42	34	99	9	0.0	N/A
9-Jan-11	Pangsun	286	103	-12.5	-31.5	29	0.1	39	16	0.0	84	0.04	2380	112	7	0.1	N/A
	Kajang	598	187	-14.0	-25.2	201	0.3	59	23	4.3	237	1.25	6698	108	623	0.2	67
	Dengkil	682	273	-13.1	-25.4	136	0.8	50	21	0.1	178	0.46	5026	99	116	0.1	79
	Semenyih	418	263	-12.3	-26.8	65	0.3	310	13	0.1	112	0.10	3163	110	62	0.1	58
	Groundwater	398	38	-22.0	-26.9	8	0.0	13	4	0.2	32	0.18	901	99	9	0.0	N/A
22-Jan-11	Pangsun	313	114	-12.5	-30.0	31	1.5	27	18	0.0	49	0.03	1371	117	7	0.1	19
	Kajang	627	244	-14.1	-24.5	216	0.6	53	24	5.7	234	1.85	6606	118	N/A	0.2	266
	Dengkil	563	178	-13.9	-26.0	147	0.1	52	22	0.0	186	0.03	5251	96	128	0.1	26
	Semenyih	370	233	-12.2	-26.6	61	0.6	250	14	0.1	104	0.83	2927	112	55	0.1	33
	Groundwater					8	0.1	13	4	0.2	32	0.18	903	101	9	0.0	N/A
12-Feb-11	Pangsun	249	174	-12.6	-29.1	40	0.3	40	16	0.0	50	0.45	1414	110	24	0.1	6
	Kajang	524	375	-13.7	-25.3	144	0.3	86	18	0.1	140	1.81	3948	95	138	0.1	57
	Dengkil	663	329	-13.1	-27.1	106	0.5	45	17	0.2	157	0.58	4440	82	98	0.1	41
	Semenyih	356	234	-12.5	-28.8	94	0.9	43	14	0.1	99	1.89	2804	90	101	0.1	36
	Groundwater	603	108	-23.0	-29.3	21	0.1	15	6	0.2	40	0.46	1142	101	20	0.0	6
26-Feb-11	Pangsun	255	173	-12.6	-29.0	26	0.3	39	16	0.0	42	0.04	1172	109	7	0.1	N/A
	Kajang	538	291	-14.7	-27.0	134	1.5	111	16	0.2	139	0.87	3917	109	121	0.1	60
	Dengkil	518	287	-13.7	-27.7	108	1.9	44	15	0.1	126	0.97	3542	79	106	0.1	74
	Semenyih	346	269	-12.3	-28.7	73	1.4	43	13	0.0	104	0.14	2943	92	76	0.1	43
	Groundwater	489	109	-23.1	-29.6	12	0.1	21	5	0.2	34	0.15	952	96	9	0.0	N/A
13-Mar-11	Pangsun	261	176	-12.4	-29.2	26	0.2	39	16	0.0	41	0.03	1151	110	6	0.1	N/A
	Kajang	641	288	-14.1	-28.3	138	0.3	127	15	0.0	117	0.08	3291	85	112	0.1	60
	Dengkil	399	443	-13.6	-22.3	88	1.8	38	14	0.1	106	0.27	2995	85	79	0.1	67
	Semenyih	302	259	-12.6	-28.9	58	1.4	38	12	0.0	86	0.26	2435	85	63	0.1	24
	Groundwater	536	128	-22.2	-29.7	16	0.1	25	7	0.2	38	0.19	1083	107	10	0.0	N/A
27-Mar-11	Pangsun	290	188	-12.4	-29.2	49	0.4	43	18	0.0	56	0.79	1572	118	33	0.1	8
	Kajang	658	250	-15.2	-28.3	127	0.9	115	15	0.1	141	1.27	3974	110	108	0.1	54
	Dengkil	441	277	-13.3	-27.5	113	0.8	43	15	0.1	104	1.36	2928	84	106	0.1	60
	Semenyih	328	258	-13.3	-28.6	81	1.3	43	14	0.0	95	1.41	2688	94	88	0.1	34
	Groundwater	535	158	-22.5	-29.2	31	0.1	26	7	0.2	45	0.83	1271	103	29	0.0	9
10-Apr-11	Pangsun	298	188	-12.7	-29.3	29	0.5	44	18	0.0	47	0.07	1317	123	7	0.1	N/A
	Kajang	713	304	-14.1	-28.2	170	0.2	159	19	0.1	160	0.44	4504	107	140	0.1	73
	Dengkil	511	1228	-15.5	-18.8	102	0.9	46	15	0.0	110	1.07	3098	80	89	0.1	72
	Semenyih	338	286	-13.3	-28.5	65	1.5	43	13	0.0	96	1.83	2698	96	70	0.1	35
	Groundwater	622	134	-23.8	-29.7	14	0.1	24	6	0.2	39	0.32	1105	103	12	0.0	N/A
24-Apr-11	Pangsun	289	78	-14.4	-28.3	62	2.7	58	40	0.0	94	N/A	2658	225	7	0.1	18
	Kajang	175	139	-14.7	-27.6	455	0.5	110	53	11.5	477	3.69	13456	226	639	0.4	256
	Dengkil	753	140	-18.7	-28.4	307	N/A	105	49	0.0	381	0.13	10740	173	121	0.3	83
	Semenyih	282	149	-12.1	-30.2	150	0.0	770	33	0.0	259	N/A	7297	217	68	0.2	88
	Groundwater	266	53	-19.8	-31.8	13	N/A	30	10	0.4	61	0.27	1732	193	8	0.1	N/A
7-May-11	Pangsun	302	11371	-15.3	-25.8	45	N/A	5300	30	0.0	6149	0.86	173442	193	9	0.1	N/A
	Kajang	871	13835	-20.1	-25.6	188	N/A	5564	27	0.0	5710	0.25	161059	193	69	0.2	N/A
	Dengkil	678	7752	-15.8	-25.5	225	0.2	3478	34	0.0	4095	0.35	115496	196	87	0.2	127
	Semenyih	358	13187	-18.1	-26.6	89	0.0	3418	22	0.0	3785	0.06	106768	200	49	0.2	N/A
	Groundwater	428	14403	-23.0	-25.9	19	N/A	5346	10	0.4	6212	0.79	175207	168	8	0.1	N/A
21-May-11	Pangsun	225	367	-14.6	-29.5	45	1.1	80	31	0.1	79	0.01	2217	197	7	0.1	N/A
	Kajang	388	616	-9.8	-27.0	5	0.0	3	1	0.1	13	0.80	355	1	36	0.0	51
	Dengkil	360	456	-9.6	-29.3	213	N/A	85	31	0.2	252	4.71	7105	149	108	0.2	28
	Semenyih	338	495	-7.0	-29.3	195	N/A	115	31	0.0	214	2.83	6025	160	95	0.2	N/A
	Groundwater	280	292	-17.9	-30.2	56	N/A	43	18	0.4	83	1.16	2344	189	23	0.1	N/A
12-Jun-11	Pangsun	179	327	-10.9	-30.1	117	N/A	87	37	0.0	110	3.02	3113	202	40	0.1	N/A
	Kajang	492	745	-10.6	-25.1	347	N/A	314	39	0.0	295	0.23	8334	192	133	0.3	122
	Dengkil	478	521	-9.6	-28.7	234	2.5	96	41	0.5	341	1.55	9619	143	103	0.2	55
	Semenyih	279	487	-7.9	-29.5	118	N/A	86	26	0.0	181	0.25	5095	163	56	0.2	19
	Groundwater	316	298	-19.9	-30.5	20	N/A	28	11	0.4	67	0.23	1887	188	1	0.1	N/A
26-Jun-11	Pangsun	320	106	-14.5	-31.5	52	N/A	51	35	0.0	82	0.83	2304	216	7	0.1	N/A
	Kajang	993	153	-19.8	-29.2	217	N/A	896	32	0.0	254	0.24	7167	215	77	0.2	45
	Dengkil	729	155	-15.4	-29.0	244	N/A	203	37	0.0	312	0.12	8791	206	94	0.2	108
	Semenyih	384	143	-17.2	-28.6	98	1.2	328	26	0.0	202	0.05	5703	214	52	0.2	55
	Groundwater	498	26	-23.9	-32.4	22	N/A	30	12	0.5	69	0.74	1955	193	7	0.1	N/A

Date	Location	[DIC] (μM)	[DOC] (μM)	$\delta^{13}C$ DIC (‰)	$\delta^{13}C$ DOC (‰)	Ca (μM)	Fe (μM)	K (μM)	Mg (μM)	Mn (μM)	Na (μM)	Zn (μM)	Cl- (μM)	Si (μM)	SO_4 (μM)	Sr (μM)	NO_3 (μM)
16-Jul-11	Pangsun	242	223	-13.5	-37.9	57	0.1	56	32	0.0	100	0.02	2822	N/A	6	0.1	N/A
	Kajang	438	285	-14.9	-35.8	270	0.1	289	26	0.0	284	0.06	8014	N/A	124	0.2	54
	Dengkil	647	333	-16.8	-35.1	215	0.1	101	32	0.0	263	0.09	7414	N/A	115	0.2	70
	Semenyih	278	302	-16.5	-35.9	124	0.3	111	25	0.0	306	0.87	8624	N/A	83	0.2	61
	Groundwater	233	191	-20.9	-38.6	23	0.1	41	9	0.8	75	1.68	2108	N/A	7	0.1	N/A
30-Jul-11	Pangsun	55	190	-7.3	-31.5	56	0.2	57	32	0.0	102	0.01	2863	N/A	3	0.1	N/A
	Kajang	148	403	-9.6	-25.2	259	0.2	286	24	0.0	290	0.20	8181	N/A	112	0.2	N/A
	Dengkil	99	443	-7.2	-20.0	212	0.6	102	31	0.0	267	0.11	7525	N/A	112	0.2	14
	Semenyih	83	404	-9.8	-24.0	126	0.2	111	26	0.0	312	0.08	8797	N/A	83	0.2	1
	Groundwater	80	143	-16.2	-38.1	23	0.1	41	9	0.8	75	1.53	2103	N/A	7	0.1	N/A
18-Aug-11	Pangsun	258	57	-13.5	-27.7	58	0.1	58	32	0.0	98	0.96	2775	N/A	9	0.1	N/A
	Kajang	391	103	-12.5	-26.0	241	0.3	257	29	0.0	274	0.17	7725	N/A	97	0.2	72
	Dengkil	488	148	-13.5	-26.3	211	0.7	303	32	0.2	436	0.07	12309	N/A	90	0.2	117
	Semenyih	303	113	-16.3	-27.0	113	1.4	234	24	0.1	284	0.04	8001	N/A	71	0.2	74
	Groundwater	150	16	-16.1	-25.8	31	0.2	43	10	0.6	81	1.33	2274	N/A	12	0.1	2
26-Aug-11	Pangsun	222	138	-11.6	-36.5	57	0.1	57	33	0.0	102	0.03	2880	N/A	5	0.1	N/A
	Kajang	389	183	-13.9	-32.9	270	0.1	290	26	0.0	285	0.06	8039	N/A	123	0.2	58
	Dengkil	125	103	-9.6	-28.6	214	0.2	101	32	0.0	264	0.09	7447	N/A	114	0.2	75
	Semenyih	308	257	-15.7	-29.2	124	1.3	111	25	0.1	307	0.05	8662	N/A	82	0.2	44
	Groundwater	231	17	-17.6	-28.4	23	0.1	41	9	0.8	75	1.70	2116	N/A	7	0.1	N/A
13-Sep-11	Pangsun	223	71	-10.6	-27.5	73	0.3	65	32	0.0	105	0.05	2961	N/A	16	0.1	0
	Kajang	543	151	-11.7	-26.4	317	0.2	336	34	0.0	368	0.04	10386	N/A	110	0.3	138
	Dengkil	549	178	-14.9	-25.9	279	1.0	841	37	0.1	422	0.06	11912	N/A	124	0.3	148
	Semenyih	209	148	-8.8	-26.8	122	2.0	873	25	0.0	277	0.03	7802	N/A	64	0.2	37
	Groundwater	165	26	-16.6	-25.7	34	0.2	52	9	0.7	79	1.72	2220	N/A	15	0.1	1
30-Sep-11	Pangsun	236	262	-9.4	-28.0	84	0.2	64	31	0.0	105	0.03	2973	N/A	25	0.1	N/A
	Kajang	533	293	-12.1	-32.5	292	0.5	310	32	0.1	329	0.06	9270	N/A	103	0.2	80
	Dengkil	618	303	-11.8	-28.0	267	0.3	892	36	0.0	371	0.05	10472	N/A	117	0.2	109
	Semenyih	233	212	-10.3	-30.4	146	0.3	615	26	0.0	236	0.06	6646	N/A	72	0.2	16
	Groundwater	172	118	-19.0	-35.1	68	0.2	66	11	0.3	87	1.68	2460	N/A	36	0.1	N/A
16-Oct-11	Pangsun	193	228	-8.8	-32.7	55	0.3	56	33	0.0	97	0.01	2744	N/A	7	0.1	N/A
	Kajang	750	280	-13.0	-28.8	321	0.2	333	34	0.0	364	0.03	10278	N/A	107	0.3	115
	Dengkil	767	294	-13.0	-27.1	289	0.2	991	37	0.0	401	0.05	11308	N/A	128	0.3	128
	Semenyih	316	275	-11.4	-31.8	123	0.6	879	25	0.0	277	0.05	7823	N/A	61	0.2	17
	Groundwater	178	91	-19.8	-28.2	17	0.2	56	8	0.4	71	2.19	2013	N/A	9	0.1	1
29-Oct-11	Pangsun	373	180	-15.3	-29.3	165	7.3	72	38	0.1	168	1.81	4732	N/A	51	0.2	60
	Kajang	1685	339	-15.0	-27.7	528	1.1	130	50	2.9	582	5.79	16427	N/A	203	0.4	N/A
	Dengkil	1067	225	-14.7	-27.2	369	0.4	116	47	0.1	464	0.91	13097	N/A	139	0.3	203
	Semenyih	505	179	-17.1	-27.6	N/A	N/A	N/A	N/A	N/A	N/A	0.00	N/A	N/A	N/A	0.0	N/A
	Groundwater	368	170	-18.6	-28.4	145	1.7	55	13	0.1	136	1.10	3839	N/A	29	0.1	N/A
12-Nov-11	Pangsun	335	171	-15.1	-29.9	81	14.9	61	37	0.2	129	5.56	3630	N/A	10	0.2	38
	Kajang	1313	252	-15.8	-26.7	318	4.0	97	44	1.5	364	1.07	10278	N/A	117	0.3	90
	Dengkil	1049	222	-14.6	-27.3	362	0.3	113	46	0.1	447	1.06	12618	N/A	136	0.3	173
	Semenyih	503	164	-17.6	-27.7	142	0.3	102	28	0.0	295	0.55	8322	N/A	68	0.2	57
	Groundwater	348	173	-18.8	-28.6	148	1.0	55	13	0.2	135	9.73	3801	N/A	33	0.1	N/A
26-Nov-11	Pangsun	344	186	-14.7	-30.0	121	12.0	68	38	0.2	147	6.66	4156	N/A	28	0.2	47
	Kajang	1729	314	-14.9	-26.7	511	3.5	124	48	2.5	562	3.26	15852	N/A	195	0.4	N/A
	Dengkil	1151	220	-14.0	-26.9	368	0.2	115	47	0.0	459	0.98	12946	N/A	139	0.3	181
	Semenyih	407	183	-17.7	-28.2	102	0.1	82	21	0.0	238	0.21	6726	N/A	50	0.1	41
	Groundwater	351	181	-18.9	-28.9	117	0.9	50	9	0.1	112	6.15	3162	N/A	15	0.1	N/A
17-Dec-11	Pangsun	347	173	-15.2	-30.3	124	11.2	68	37	0.2	152	9.01	4281	N/A	32	0.2	40
	Kajang	1025	199	-18.2	-26.6	386	0.2	92	37	0.1	429	10.61	12090	N/A	154	0.3	14
	Dengkil	879	224	-14.5	-27.8	370	0.4	115	48	0.0	453	1.39	12778	N/A	143	0.3	192
	Semenyih	493	198	-16.3	-27.6	228	0.3	100	35	0.0	265	2.79	7464	N/A	97	0.3	43
	Groundwater	317	193	-19.1	-28.5	111	1.1	47	9	0.1	108	5.61	3043	N/A	14	0.1	N/A
31-Dec-11	Pangsun	344	171	-14.2	-29.8	90	13.1	60	39	0.1	133	9.63	3761	N/A	12	0.2	35
	Kajang	1706	272	-17.0	-27.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.0	N/A
	Dengkil	1355	232	-13.9	-26.4	416	0.1	131	56	0.0	577	N/A	16283	N/A	160	0.4	263
	Semenyih	509	168	-17.3	-27.0	129	0.1	104	28	0.0	313	N/A	8842	N/A	64	0.2	60
	Groundwater	684	533	-23.0	-29.8	146	0.7	52	12	0.1	131	3.74	3695	N/A	25	0.1	17

Appendix 4: Geochemical data from the Kelantan River. (carbon data measured at the G.G. Hatch Laboratory, cation data measured via ICP-AES, anion data measured via ion chromatograph).

Date	Location	[DIC] (μM)	[DOC] (μM)	$\delta^{13}C$ DIC (‰)	$\delta^{13}C$ DOC (‰)	Ca (μM)	Fe (μM)	K (μM)	Mg (μM)	Mn (μM)	Na (μM)	Zn (μM)	Cl- (μM)	Si (μM)	SO_4 (μM)	Sr (μM)	NO_3 (μM)
25-May-10	Tanah Merah	274	259	-12.7	-23.2	117	3.0	68	45	0.2	148	N/A	67	N/A	14	0.3	N/A
	Pasir Mas	273	290	-13.4	-26.8	105	2.3	59	41	0.0	144	N/A	73	N/A	15	0.3	N/A
	Kota Bharu	N/A	N/A	N/A	N/A	67	8.7	66	52	0.0	183	N/A	N/A	N/A	0	0.3	N/A
	Groundwater	1234	158	-16.4	-24.6	35	2.7	59	15	0.5	413	N/A	278	N/A	51	0.2	N/A
12-Jun-10	Tanah Merah	368	618	-11.0	-25.9	121	1.3	127	45	0.1	133	N/A	130	N/A	12	0.3	N/A
	Pasir Mas	306	421	-11.4	-28.0	114	1.6	82	42	0.1	139	N/A	96	N/A	13	0.3	N/A
	Kota Bharu	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0.0	N/A	N/A	N/A	N/A	0	0.0	N/A
	Groundwater	1442	N/A	-17.3	-27.5	36	0.1	72	16	0.5	412	N/A	2849	N/A	51	0.2	N/A
26-Jun-10	Tanah Merah	334	N/A	N/A	N/A	91	2.4	71	35	0.0	108	N/A	79	N/A	20	0.2	N/A
	Pasir Mas	233	491	-12.5	-25.4	96	3.3	130	36	0.1	92	N/A	133	N/A	21	0.2	N/A
	Kota Bharu	N/A	430	-18.5	-29.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0.0	N/A
	Groundwater	1463	N/A	N/A	N/A	41	1.0	2560	15	0.6	369	N/A	297	N/A	50	0.2	N/A
10-Jul-10	Tanah Merah	122	279	-15.6	-27.7	127	2.4	1224	40	0.1	120	0.03	1278	N/A	13	0.3	N/A
	Pasir Mas	145	530	-11.9	-25.0	136	0.2	2201	44	0.0	109	N/A	2332	N/A	15	0.3	N/A
	Kota Bharu	N/A	283	-12.5	-28.6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0.0	N/A
	Groundwater	412	N/A	N/A	N/A	45	1.0	1273	21	0.7	533	0.31	1621	N/A	76	0.2	N/A
24-Jul-10	Tanah Merah	87	405	-12.1	-26.4	133	1.6	66	45	0.1	126	0.02	85	N/A	15	0.3	N/A
	Pasir Mas	109	449	-13.2	-25.3	119	0.3	85	40	0.0	130	0.01	113	N/A	15	0.2	N/A
	Kota Bharu	N/A	375	-12.7	-26.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	0.0	N/A
	Groundwater	375	N/A	N/A	N/A	35	0.3	76	16	0.5	452	0.45	333	N/A	56	0.2	N/A
8-Aug-10	Tanah Merah	168	244	-15.2	-27.9	167	1.3	95	46	0.2	200	0.38	136	N/A	14	0.3	N/A
	Pasir Mas	124	689	-15.7	-25.0	135	1.3	47	39	N/A	103	0.11	54	N/A	13	0.2	N/A
	Kota Bharu	133	354	-15.0	-27.0	0	N/A	N/A	N/A	N/A	N/A	0.00	N/A	N/A	0	0.0	N/A
	Groundwater	395	413	-13.9	-26.5	31	0.3	55	14	N/A	384	0.10	280	N/A	46	0.2	N/A
21-Aug-10	Tanah Merah	122	419	-15.8	-28.0	134	0.7	39	49	0.0	128	0.01	49	N/A	12	0.3	N/A
	Pasir Mas	117	226	-13.4	-26.9	130	1.9	37	48	0.0	140	0.07	66	N/A	14	0.3	N/A
	Kota Bharu	175	435	-13.5	-21.0	0	N/A	N/A	N/A	N/A	N/A	0.00	46	N/A	12	0.0	N/A
	Groundwater	389	490	-11.8	-25.3	33	0.2	58	16	0.0	451	0.17	312	N/A	51	0.2	N/A
3-Sep-10	Tanah Merah	440	441	-15.7	-27.0	53	3.1	16	26	0.0	89	0.68	115	N/A	10	0.1	3
	Pasir Mas	427	438	-15.7	-27.7	45	5.8	17	20	0.8	63	0.06	69	N/A	10	0.1	16
	Kota Bharu	N/A	559	-16.8	-25.2	45	4.9	16	20	0.0	69	0.00	67	N/A	10	0.1	5
	Groundwater	1575	N/A	N/A	N/A	22	1.9	33	10	0.4	282	0.11	343	N/A	56	0.1	3
17-Sep-10	Tanah Merah	449	362	-15.0	-26.6	53	5.3	15	26	0.3	88	0.04	109	N/A	9	0.1	5
	Pasir Mas	399	491	-15.0	-27.9	45	5.5	17	20	0.2	64	0.05	67	N/A	10	0.1	16
	Kota Bharu	N/A	501	-16.7	-25.3	45	3.6	16	20	0.0	63	0.05	64	N/A	9	0.1	14
	Groundwater	1632	N/A	N/A	N/A	20	2.9	31	10	0.3	273	0.06	333	N/A	44	0.1	N/A
2-Oct-10	Tanah Merah	838	284	-14.8	-27.2	0	N/A	N/A	N/A	N/A	N/A	0.00	215	N/A	26	0.0	9
	Pasir Mas	444	644	-15.7	-26.8	0	N/A	N/A	N/A	N/A	N/A	0.00	98	N/A	13	0.0	N/A
	Kota Bharu	N/A	388	-18.9	-27.3	0	N/A	N/A	N/A	N/A	N/A	0.00	N/A	N/A	0	0.0	0
	Groundwater	1399	N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A	0.00	182	N/A	34	0.0	4
16-Oct-10	Tanah Merah	790	193	-20.4	-28.8	149	26.6	116	82	0.2	191	0.01	208	117	24	0.4	N/A
	Pasir Mas	429	725	-15.3	-26.8	66	14.8	54	33	0.2	106	0.01	96	95	12	0.2	N/A
	Kota Bharu	N/A	394	-19.1	-27.8	61	0.5	49	31	0.0	77	0.30	64	83	11	0.2	N/A
	Groundwater	1264	N/A	N/A	N/A	27	0.0	48	13	0.4	264	N/A	173	202	33	0.1	15
8-Jan-11	Tanah Merah	376	186	-20.1	-28.5	122	0.4	36	50	0.9	128	N/A	36	266	9	0.3	7
	Pasir Mas	388	218	-13.0	-26.8	122	0.9	36	50	0.9	133	0.05	40	265	9	0.3	5
	Kota Bharu	398	243	-12.9	-26.2	122	0.4	36	49	0.9	130	N/A	40	265	9	0.3	7
	Groundwater	1340	195	-13.2	-27.8	27	0.9	52	15	0.5	300	0.16	187	183	38	0.2	4
22-Jan-11	Tanah Merah	393	152	-20.3	-28.4	123	0.5	37	50	0.9	132	N/A	38	265	9	0.3	7
	Pasir Mas	386	351	-13.1	-23.3	121	0.5	36	49	0.9	130	0.01	39	261	9	0.3	7
	Kota Bharu	387	198	-13.1	-28.6	123	0.7	38	50	0.9	137	0.04	39	263	9	0.3	7
	Groundwater	1671	206	-13.1	-27.3	27	1.0	53	16	0.5	305	0.14	187	181	38	0.2	4
8-Feb-11	Tanah Merah	395	227	-20.8	-27.4	122	0.4	35	50	0.9	129	N/A	N/A	267	0	0.3	0
	Pasir Mas	385	245	-13.4	-26.5	121	0.4	35	49	0.9	129	N/A	36	262	9	0.3	6
	Kota Bharu	387	195	-13.2	-27.9	26	0.7	51	15	0.5	299	0.13	36	180	9	0.2	6
	Groundwater	1574	191	-13.2	-27.0	0	N/A	0	0	N/A	N/A	0.00	186	0	38	0.0	4
22-Feb-11	Tanah Merah	390	140	-20.7	-28.3	124	0.5	36	49	0.6	132	N/A	35	262	9	0.3	7
	Pasir Mas	405	214	-13.1	-27.0	122	0.4	35	49	0.9	130	N/A	34	261	9	0.3	7
	Kota Bharu	401	211	-13.1	-28.0	123	0.4	36	49	0.9	132	N/A	37	266	9	0.3	7
	Groundwater	1601	221	-13.1	-27.1	0	N/A	0	0	N/A	N/A	N/A	N/A	0	0	0.0	0
5-Mar-11	Tanah Merah	395	190	-20.5	-27.2	121	0.5	36	49	0.8	131	N/A	37	261	9	0.3	8
	Pasir Mas	379	194	-13.1	-28.1	124	0.4	36	49	0.9	132	0.02	37	263	9	0.3	6
	Kota Bharu	642	199	-13.0	-28.1	122	0.4	38	49	0.9	136	0.04	41	261	9	0.3	8
	Groundwater	1787	365	-17.8	-28.8	27	2.8	52	15	0.5	306	2.17	186	180	38	0.2	4
19-Mar-11	Tanah Merah	395	196	-20.8	-27.8	121	0.3	34	48	0.8	129	N/A	35	260	9	0.3	6
	Pasir Mas	390	220	-13.1	-27.9	121	0.6	36	48	0.9	133	0.03	40	257	9	0.3	7
	Kota Bharu	405	182	-13.0	-28.0	0	0.0	0	0	N/A	N/A	N/A	14	0	2	0.0	5
	Groundwater	1540	207	-13.0	-27.5	122	0.7	36	50	0.9	133	0.02	38	265	9	0.3	7
2-Apr-11	Tanah Merah	683	147	-20.6	-28.6	193	5.7	79	63	5.9	294	0.08	238	215	59	0.4	4
	Pasir Mas	680	265	-13.8	-25.1	193	3.8	80	63	5.9	296	0.04	241	215	58	0.4	4
	Kota Bharu	743	706	-13.4	-22.4	194	3.2	81	63	5.9	297	0.05	243	215	58	0.4	N/A
	Groundwater	1260	505	-14.4	-24.0	63	0.1	136	51	2.2	389	0.51	311	125	42	0.2	7

Date	Location	[DIC] (μM)	[DOC] (μM)	$\delta^{13}C$ DIC (‰)	$\delta^{13}C$ DOC (‰)	Ca (μM)	Fe (μM)	K (μM)	Mg (μM)	Mn (μM)	Na (μM)	Zn (μM)	Cl- (μM)	Si (μM)	SO_4 (μM)	Sr (μM)	NO_3 (μM)
16-Apr-11	Tanah Merah	647	229	-18.4	-27.4	196	2.2	81	63	5.8	299	0.19	243	215	59	0.4	4
	Pasir Mas	733	534	-13.5	-22.6	194	4.7	81	64	5.7	301	0.05	245	216	59	0.4	4
	Kota Bharu	740	415	-14.6	-26.9	196	5.7	81	63	5.7	296	0.05	243	214	58	0.4	N/A
	Groundwater	1126	311	-13.8	-26.2	62	N/A	135	51	2.2	390	0.96	309	125	41	0.2	7
7-May-11	Tanah Merah	722	235	-17.6	-26.3	194	3.4	81	63	5.1	301	0.33	249	214	59	0.4	N/A
	Pasir Mas	661	390	-13.3	-25.7	0	0.0	N/A	N/A	N/A	N/A	N/A	N/A	0	0	0.0	0
	Kota Bharu	731	688	-12.9	-22.2	196	0.5	81	64	4.0	299	0.04	243	215	59	0.4	N/A
	Groundwater	1171	649	-13.5	-22.8	63	0.1	136	52	2.2	390	0.29	309	125	42	0.2	7
21-May-11	Tanah Merah	672	201	-18.1	-27.0	197	1.0	84	64	5.8	308	0.06	256	216	59	0.4	4
	Pasir Mas	700	351	-12.9	-23.9	195	1.7	80	63	3.8	296	0.05	243	213	59	0.4	4
	Kota Bharu	688	555	-13.4	-22.6	195	1.4	81	64	5.8	299	0.02	243	216	59	0.4	4
	Groundwater	1371	664	-13.1	-22.1	64	N/A	160	52	2.1	407	0.36	334	125	41	0.2	7
4-Jun-11	Tanah Merah	694	671	-20.0	-30.2	195	5.7	82	64	5.9	302	92.61	249	216	59	26.4	4
	Pasir Mas	687	463	-13.7	-23.9	-1	N/A	2	1	0.0	13	0.13	14	0	2	0.5	5
	Kota Bharu	708	629	-13.2	-22.5	141	0.8	43	39	0.0	149	0.01	49	178	14	0.3	2
	Groundwater	1149	354	-13.8	-26.3	138	2.3	41	39	0.0	146	0.03	46	182	4	0.3	2
18-Jun-11	Tanah Merah	654	217	-17.6	-27.2	140	0.2	40	42	0.0	146	0.04	44	184	13	0.3	0
	Pasir Mas	725	289	-13.4	-24.9	94	3.6	60	30	0.9	108	0.35	77	145	14	0.2	16
	Kota Bharu	665	398	-13.8	-24.6	92	1.9	49	29	0.1	74	0.05	48	146	11	0.2	15
	Groundwater	1129	460	-13.0	-24.2	140	2.5	40	39	0.0	145	0.00	42	181	13	0.3	0
2-Jul-11	Tanah Merah	1058	218	-17.6	-27.0	94	2.8	52	29	3.7	81	0.17	51	150	13	0.2	15
	Pasir Mas	1204	319	-17.5	-27.7	93	3.7	50	30	0.1	77	0.04	49	153	13	0.2	14
	Kota Bharu	2315	321	-17.8	-26.4	139	1.1	40	39	0.0	145	0.02	43	180	13	0.3	0
	Groundwater	1141	804	-16.2	-26.9	94	5.0	52	30	0.1	79	0.04	51	154	14	0.2	14
16-Jul-11	Tanah Merah	253	363	-17.6	-27.8	143	0.4	43	41	0.0	160	0.11	53	181	14	0.3	1
	Pasir Mas	256	245	-11.9	-26.9	147	1.8	46	46	0.0	163	0.03	58	187	13	0.3	8
	Kota Bharu	2248	244	-12.2	-28.4	93	4.3	49	30	0.1	74	0.02	47	152	13	0.2	13
	Groundwater	2086	403	-17.3	-26.7	143	0.8	43	40	0.0	150	0.03	46	180	13	0.3	1
6-Aug-11	Tanah Merah	258	483	-17.3	-26.6	49	17.9	71	23	0.9	653	0.17	316	182	27	0.3	0
	Pasir Mas	102	220	-12.0	-28.2	93	4.5	49	29	0.2	75	0.05	46	152	13	0.2	13
	Kota Bharu	258	372	-9.8	-29.4	94	2.5	53	30	0.3	84	0.11	53	150	13	0.2	14
	Groundwater	104	277	-10.8	-27.8	77	3.0	63	27	1.2	406	0.17	200	167	24	0.2	5
20-Aug-11	Tanah Merah	97	380	-8.8	-29.4	141	0.9	42	39	0.0	149	0.06	46	181	13	0.3	1
	Pasir Mas	321	353	-9.1	-29.3	95	2.6	55	30	0.1	94	0.06	63	149	13	0.2	14
	Kota Bharu	80	303	-14.3	-29.5	49	20.9	72	23	0.9	655	0.17	316	179	27	0.3	N/A
	Groundwater	97	358	-11.2	-29.4	94	3.3	52	29	0.2	85	0.05	55	150	14	0.2	14
3-Sep-11	Tanah Merah	247	449	-10.0	-28.7	50	23.5	71	24	0.9	653	0.12	314	182	27	0.3	0
	Pasir Mas	246	223	-11.6	-27.6	94	4.6	50	29	0.1	78	0.04	52	154	13	0.2	13
	Kota Bharu	250	242	-11.1	-27.9	96	4.1	55	30	0.1	90	0.03	61	150	14	0.2	15
	Groundwater	246	193	-12.6	-27.6	97	2.1	56	30	0.3	111	0.33	68	151	20	0.2	24
17-Sep-11	Tanah Merah	256	784	-12.5	-15.8	95	5.1	53	29	0.1	86	0.05	55	151	13	0.2	14
	Pasir Mas	2168	226	-11.3	-28.1	83	0.1	175	51	1.3	467	0.33	348	155	48	0.3	77
	Kota Bharu	243	703	N/A	-28.0	10	0.1	1	0	0.0	5	0.27	5	2	6	0.0	N/A
	Groundwater	249	224	-11.6	-28.2	85	0.1	174	51	0.1	461	0.25	346	156	50	0.3	151

Appendix 5: Ancillary aquatic chemistry data from the Langat River (data from Malaysian Dept. of Environment).

Location	Sampling Date	DO (ppm)	BOD (ppm)	COD (ppm)	SS (ppm)	pH	Water Temperature (^oC)
Pangsun	10-Jan-10	7.43	2	7	6	7.33	28.48
	2-Mar-10	7.97	1	5	15	7.41	27.75
	6-May-10	8.01	4	11	4	7.4	27.83
	13-Aug-10	7.59	2	5	2	7.14	28.2
	3-Sep-10	7.69	2	5	1	7.41	27.87
	4-Oct-10	7.51	2	5	6	7.42	27.7
	5-Jan-11	8.59	2	5	2	7.58	25.56
	2-Mar-11	6.28	2	6	2	7.39	28.84
	5-May-11	8.10	2	5	8	7.2	27.42
	4-Aug-11	8.13	4	14	112	7.29	25.89
	12-Sep-11	8.21	2	8	2	7.59	27.13
	7-Oct-11	8.61	2	5	5	7.64	26.32
Kajang	5-Jan-10	5.61	7	20	331	6.98	27.57
	3-Feb-10	5.46	7	22	310	7.07	29.28
	2-Mar-10	6.10	3	13	115	6.95	29.59
	5-Apr-10	4.86	6	20	159	6.93	30.08
	18-Apr-10	5.90	8	32	749	7.07	27.44
	6-May-10	4.87	3	7	130	6.93	30.68
	7-Jun-10	5.09	9	21	119	7.1	30.25
	5-Jul-10	6.22	8	25	287	7.04	25.01
	13-Aug-10	3.10	7	16	150	6.6	29.3
	6-Sep-10	4.39	8	22	258	7.04	27.16
	5-Oct-10	6.08	6	25	282	7.29	27.53
	18-Oct-10	4.76	8	18	112	7.08	27.64
	7-Jan-11	5.42	5	15	149	7.13	24.89
	8-Feb-11	6.71	8	30	228	7.00	26.2
	3-Mar-11	6.48	2	10	228	7.00	26.58
	5-Apr-11	5.72	8	36	368	7.05	27.76
	5-May-11	6.81	8	44	698	6.93	27.9
	6-Jun-11	6.28	5	17	118	7.06	27.56
	5-Jul-11	4.83	6	20	117	6.87	28.31
	17-Jul-11	4.96	4	12	74	6.98	29.59
	4-Aug-11	5.61	5	24	394	7.03	26.33
	12-Sep-11	6.51	3	11	153	7.15	26.98
	5-Oct-11	6.43	3	7	120	7.26	26.99
Dengkil	5-Jan-10	6.17	4	16	209	6.84	29.05
	3-Feb-10	5.68	4	17	58	7.07	30.66
	3-Mar-10	5.28	3	15	104	6.93	30.25
	6-Apr-10	5.28	5	14	125	6.9	30.94
	18-Apr-10	4.79	6	27	278	6.96	28.11
	6-May-10	4.47	9	18	457	6.78	28.32
	7-Jun-10	5.73	4	18	199	7.1	30.45
	5-Jul-10	6.04	5	12	190	7.14	27.74
	12-Aug-10	5.53	6	15	88	6.56	30.83
	6-Sep-10	5.44	3	10	125	7	27.08
	4-Oct-10	5.47	5	29	339	7.05	28.93
	18-Oct-10	5.61	5	11	65	6.96	29.93
	5-Jan-11	5.48	3	11	345	6.85	28.08
	8-Feb-11	6.19	5	14	191	6.87	28.43
	4-Mar-11	6.24	3	16	349	6.87	27.71
	5-Apr-11	5.92	6	11	229	7.06	29.52
	6-May-11	5.97	3	11	111	6.97	29.13
	8-Jun-11	6.12	3	8	136	6.99	29.37
	5-Jul-11	5.47	5	15	55	6.79	28.78
	17-Jul-11	7.62	4	13	146	6.8	27.54
	3-Aug-11	4.83	4	15	58	6.99	29.57
	9-Sep-11	4.98	4	17	173	7.15	28.57
	5-Oct-11	6.38	3	17	78	7.28	26.69

Appendix 6: Ancillary aquatic chemistry data from the Kelantan River (data from Malaysian Dept. of Environment).

Location	*Sampling Date*	*DO (ppm)*	*BOD (ppm)*	*COD (ppm)*	*SS (ppm)*	*pH*	*Water Temperature (^{o} C)*
Tanah Merah	11-Feb-10	6.94	1	5	79	7.83	28.87
	21-Apr-10	6.64	2	16	199	6.67	30.03
	25-Jun-10	6.66	12	35	682	6.2	27.24
	24-Aug-10	6.97	2	5	80	6.69	29.31
	22-Oct-10	6.60	2	7	160	7.11	27.76
	21-Feb-11	6.78	2	7	65	6.26	26.6
	21-Apr-11	6.10	2	5	191	6.55	29.03
	23-Jun-11	6.60	2	5	103	7.38	28.13
	18-Aug-11	6.80	3	15	243	7.12	27.08
	24-Oct-11	6.98	6	31	180	6.56	25.23
Kota Bharu	21-Feb-10	7.00	3	9	29	7.7	27.8
	23-Apr-10	5.84	3	8	215	6.73	32.6
	25-Jun-10	7.12	2	5	264	7.08	28.47
	24-Aug-10	6.96	2	5	105	7.21	29.02
	22-Oct-10	6.29	2	5	81	7.07	28.61
	22-Feb-11	6.88	4	13	48	6.34	26.73
	21-Apr-11	5.90	2	5	105	6.04	28.6
	24-Jun-11	6.25	8	45	166	7.41	28.06
	19-Aug-11	7.71	3	12	212	7.42	27.2
	24-Oct-11	6.75	3	13	101	6.57	25.22

Appendix 7: CO_2 and carbon flux calculations from the Dengkil sub-basin

Date	***Location***	***[CO_2] (ppmv)***	***CO_2 Evasion (g C day^{-1} m^{-2})***	***DOC Flux (g C day^{-1})***	***DIC Flux (g C day^{-1})***
16-May-10	Pangsun	N/A	N/A	N/A	N/A
	Kajang	6940	22.30	7.56E+06	2.82E+07
	Dengkil	N/A	N/A	N/A	N/A
	Semenyih	N/A	N/A	N/A	N/A
	Groundwater	N/A	N/A	N/A	N/A
07-Aug-10	Pangsun	515	0.13	N/A	N/A
	Kajang	1556	1.09	2.03E+06	1.31E+06
	Dengkil	2537	2.00	8.95E+06	3.96E+06
	Semenyih	1268	0.83	N/A	N/A
	Groundwater	1251	N/A	N/A	N/A
21-Aug-10	Pangsun	427	0.05	N/A	N/A
	Kajang	1531	1.07	3.97E+06	1.36E+06
	Dengkil	1151	0.72	3.16E+07	7.41E+06
	Semenyih	1118	0.69	N/A	N/A
	Groundwater	3332	N/A	N/A	N/A
07-Sep-10	Pangsun	1195	0.76	N/A	N/A
	Kajang	1552	1.09	1.66E+06	8.38E+05
	Dengkil	1343	0.90	N/A	N/A
	Semenyih	2230	1.72	N/A	N/A
	Groundwater	2986	N/A	N/A	N/A
25-Sep-10	Pangsun	1424	0.97	N/A	N/A
	Kajang	2100	1.60	3.55E+06	1.55E+06
	Dengkil	2019	1.52	N/A	N/A
	Semenyih	3255	2.67	N/A	N/A
	Groundwater	2604	N/A	N/A	N/A
17-Oct-10	Pangsun	4466	3.79	N/A	N/A
	Kajang	9930	8.85	1.89E+06	5.61E+06
	Dengkil	3114	2.54	N/A	N/A
	Semenyih	3489	2.88	N/A	N/A
	Groundwater	10213	N/A	N/A	N/A
31-Oct-10	Pangsun	622	0.23	N/A	N/A
	Kajang	9665	8.60	1.27E+06	5.35E+06
	Dengkil	1186	0.75	4.84E+07	6.72E+07
	Semenyih	972	0.55	N/A	N/A
	Groundwater	12431	N/A	N/A	N/A
15-Nov-10	Pangsun	5310	4.57	N/A	N/A
	Kajang	6027	5.23	N/A	N/A
	Dengkil	7806	6.88	N/A	N/A
	Semenyih	3866	3.23	N/A	N/A
	Groundwater	30840	N/A	N/A	N/A
30-Nov-10	Pangsun	4074	3.43	N/A	N/A
	Kajang	6951	6.09	N/A	N/A
	Dengkil	3903	3.27	8.01E+06	7.05E+06
	Semenyih	3790	3.16	N/A	N/A
	Groundwater	11746	N/A	N/A	N/A

Date	*Location*	*[CO_2] (ppmv)*	*CO_2 Evasion ($g\ C\ day^{-1}\ m^{-2}$)*	*DOC Flux ($g\ C\ day^{-1}$)*	*DIC Flux ($g\ C\ day^{-1}$)*
5-Dec-10	Pangsun	1648	1.18	N/A	N/A
	Kajang	2005	1.51	N/A	N/A
	Dengkil	905	0.49	1.01E+07	1.66E+07
	Semenyih	1111	0.68	N/A	N/A
	Groundwater	2950	N/A	N/A	N/A
19-Dec-10	Pangsun	1692	1.22	N/A	N/A
	Kajang	4021	3.38	9.80E+05	3.48E+06
	Dengkil	3123	2.55	9.37E+06	2.00E+07
	Semenyih	1828	1.35	N/A	N/A
	Groundwater	8565	N/A	N/A	N/A
9-Jan-11	Pangsun	856	0.45	N/A	N/A
	Kajang	2052	1.55	8.13E+05	2.60E+06
	Dengkil	3014	2.44	5.83E+06	1.45E+07
	Semenyih	1915	1.43	N/A	N/A
	Groundwater	4768	N/A	N/A	N/A
22-Jan-11	Pangsun	5219	4.49	N/A	N/A
	Kajang	1706	1.23	N/A	N/A
	Dengkil	1727	1.25	4.61E+06	1.45E+07
	Semenyih	1500	1.04	N/A	N/A
	Groundwater	N/A	N/A	N/A	N/A
12-Feb-11	Pangsun	858	0.45	N/A	N/A
	Kajang	2125	1.62	N/A	N/A
	Dengkil	2333	1.81	9.70E+06	1.95E+07
	Semenyih	1627	1.16	N/A	N/A
	Groundwater	10492	N/A	N/A	N/A
26-Feb-11	Pangsun	1695	1.22	N/A	N/A
	Kajang	3106	2.53	N/A	N/A
	Dengkil	7313	6.43	1.27E+07	2.30E+07
	Semenyih	3950	3.31	N/A	N/A
	Groundwater	10004	N/A	N/A	N/A
13-Mar-11	Pangsun	732	0.33	N/A	N/A
	Kajang	3418	2.82	N/A	N/A
	Dengkil	1403	0.95	N/A	N/A
	Semenyih	843	0.43	N/A	N/A
	Groundwater	11060	N/A	N/A	N/A
27-Mar-11	Pangsun	240	-0.12	N/A	N/A
	Kajang	3620	3.01	N/A	N/A
	Dengkil	661	0.27	7.74E+06	1.23E+07
	Semenyih	263	-0.10	N/A	N/A
	Groundwater	11020	N/A	N/A	N/A
10-Apr-11	Pangsun	520	0.13	N/A	N/A
	Kajang	3602	2.99	N/A	N/A
	Dengkil	9619	8.56	5.43E+07	2.26E+07
	Semenyih	5502	4.75	N/A	N/A
	Groundwater	3256	N/A	N/A	N/A

Date	***Location***	***[CO_2] (ppmv)***	***CO_2 Evasion ($g\ C\ day^{-1}\ m^{-2}$)***	***DOC Flux ($g\ C\ day^{-1}$)***	***DIC Flux ($g\ C\ day^{-1}$)***
24-Apr-11	Pangsun	4236	3.58	N/A	N/A
	Kajang	1460	1.00	N/A	N/A
	Dengkil	6603	5.77	9.08E+06	4.89E+07
	Semenyih	5539	4.78	N/A	N/A
	Groundwater	3925	N/A	N/A	N/A
7-May-11	Pangsun	2970	2.40	N/A	N/A
	Kajang	10778	9.64	N/A	N/A
	Dengkil	3648	3.03	3.18E+08	2.78E+07
	Semenyih	3347	2.75	N/A	N/A
	Groundwater	1947	N/A	N/A	N/A
21-May-11	Pangsun	1027	0.60	N/A	N/A
	Kajang	2056	1.56	N/A	N/A
	Dengkil	4443	3.77	4.88E+07	3.86E+07
	Semenyih	2825	2.27	N/A	N/A
	Groundwater	1240	N/A	N/A	N/A
12-Jun-11	Pangsun	1928	1.44	N/A	N/A
	Kajang	3788	3.16	N/A	N/A
	Dengkil	8198	7.25	1.50E+07	1.38E+07
	Semenyih	5575	4.82	N/A	N/A
	Groundwater	4900	N/A	N/A	N/A
26-Jun-11	Pangsun	5116	4.39	N/A	N/A
	Kajang	5878	5.10	N/A	N/A
	Dengkil	12550	11.28	3.43E+06	1.61E+07
	Semenyih	7791	6.87	N/A	N/A
	Groundwater	9609	N/A	N/A	N/A
16-Jul-11	Pangsun	4602	3.92	N/A	N/A
	Kajang	6802	5.95	N/A	N/A
	Dengkil	9792	8.72	1.44E+07	2.80E+07
	Semenyih	4951	4.24	N/A	N/A
	Groundwater	4531	N/A	N/A	N/A
30-Jul-11	Pangsun	258	-0.11	N/A	N/A
	Kajang	518	0.13	N/A	N/A
	Dengkil	1045	0.62	2.42E+07	5.42E+06
	Semenyih	902	0.49	N/A	N/A
	Groundwater	751	N/A	N/A	N/A
18-Aug-11	Pangsun	1926	1.44	N/A	N/A
	Kajang	2190	1.68	N/A	N/A
	Dengkil	2626	2.09	4.20E+06	1.38E+07
	Semenyih	1753	1.28	N/A	N/A
	Groundwater	1147	N/A	N/A	N/A
26-Aug-11	Pangsun	1273	0.83	N/A	N/A
	Kajang	2089	1.59	N/A	N/A
	Dengkil	412	0.03	3.24E+06	3.95E+06
	Semenyih	765	0.36	N/A	N/A
	Groundwater	2698	N/A	N/A	N/A

Date	*Location*	*[CO_2] (ppmv)*	*CO_2 Evasion ($g\ C\ day^{-1}\ m^{-2}$)*	*DOC Flux ($g\ C\ day^{-1}$)*	*DIC Flux ($g\ C\ day^{-1}$)*
13-Sep-11	Pangsun	1212	0.78	N/A	N/A
	Kajang	2693	2.15	N/A	N/A
	Dengkil	2014	1.52	2.54E+06	7.85E+06
	Semenyih	901	0.49	N/A	N/A
	Groundwater	2521	N/A	N/A	N/A
30-Sep-11	Pangsun	1567	1.10	N/A	N/A
	Kajang	2796	2.24	N/A	N/A
	Dengkil	2323	1.80	6.52E+06	1.33E+07
	Semenyih	1073	0.65	N/A	N/A
	Groundwater	2669	N/A	N/A	N/A
16-Oct-11	Pangsun	1500	1.04	N/A	N/A
	Kajang	4217	3.56	N/A	N/A
	Dengkil	4195	3.54	6.08E+06	1.59E+07
	Semenyih	1898	1.41	N/A	N/A
	Groundwater	3122	N/A	N/A	N/A
29-Oct-11	Pangsun	3409	2.81	N/A	N/A
	Kajang	18792	17.06	N/A	N/A
	Dengkil	11334	10.15	1.11E+07	5.28E+07
	Semenyih	10191	9.09	N/A	N/A
	Groundwater	3244	N/A	N/A	N/A
12-Nov-11	Pangsun	3993	3.35	N/A	N/A
	Kajang	14801	13.36	N/A	N/A
	Dengkil	9290	8.26	5.84E+06	2.76E+07
	Semenyih	3412	2.81	N/A	N/A
	Groundwater	5403	N/A	N/A	N/A
26-Nov-11	Pangsun	2700	2.15	N/A	N/A
	Kajang	21276	19.36	N/A	N/A
	Dengkil	8949	7.94	1.72E+07	9.00E+07
	Semenyih	3451	2.85	N/A	N/A
	Groundwater	5007	N/A	N/A	N/A
17-Dec-11	Pangsun	3145	9.41	N/A	N/A
	Kajang	14134	46.74	N/A	N/A
	Dengkil	9682	31.62	N/A	N/A
	Semenyih	3979	12.24	N/A	N/A
	Groundwater	3830	11.74	N/A	N/A
31-Dec-11	Pangsun	3731	11.40	N/A	N/A
	Kajang	15808	52.42	N/A	N/A
	Dengkil	9908	32.38	N/A	N/A
	Semenyih	5390	17.04	N/A	N/A
	Groundwater	7831	25.33	N/A	N/A

Appendix 8: CO_2 and carbon flux calculations from the Kelantan basin

Date	***Location***	***[CO₂] (ppmv)***	***CO₂ Evasion (g C day⁻¹ m⁻²)***	***DOC Flux (g C day⁻¹)***	***DIC Flux (g C day⁻¹)***
25-May-10	Tanah Merah	1469	4.02	2.70E+07	2.85E+07
	Pasir Mas	1414	3.82	N/A	N/A
	Kota Bharu	935	2.03	N/A	N/A
	Groundwater	5107	17.57	N/A	N/A
12-Jun-10	Tanah Merah	1944	5.79	8.83E+07	5.26E+07
	Pasir Mas	1672	4.78	N/A	N/A
	Kota Bharu	N/A	N/A	N/A	N/A
	Groundwater	7443	26.27	N/A	N/A
26-Jun-10	Tanah Merah	1715	4.93	9.74E+07	6.62E+07
	Pasir Mas	1215	3.07	N/A	N/A
	Kota Bharu	N/A	N/A	N/A	N/A
	Groundwater	7767	27.48	N/A	N/A
10-Jul-10	Tanah Merah	639	0.93	8.03E+07	1.86E+07
	Pasir Mas	772	1.42	N/A	N/A
	Kota Bharu	N/A	N/A	N/A	N/A
	Groundwater	2096	6.35	N/A	N/A
24-Jul-10	Tanah Merah	448	0.21	9.61E+07	1.85E+07
	Pasir Mas	560	0.63	N/A	N/A
	Kota Bharu	N/A	N/A	N/A	N/A
	Groundwater	1966	5.87	N/A	N/A
8-Aug-10	Tanah Merah	857	1.74	2.52E+08	6.16E+07
	Pasir Mas	639	0.93	N/A	N/A
	Kota Bharu	667	1.03	N/A	N/A
	Groundwater	2096	6.36	N/A	N/A
21-Aug-10	Tanah Merah	622	0.87	6.18E+07	3.32E+07
	Pasir Mas	606	0.80	N/A	N/A
	Kota Bharu	878	1.82	N/A	N/A
	Groundwater	2020	6.07	N/A	N/A
3-Sep-10	Tanah Merah	2323	7.20	8.73E+07	8.78E+07
	Pasir Mas	2253	6.94	N/A	N/A
	Kota Bharu	N/A	-1.45	N/A	N/A
	Groundwater	8309	29.50	N/A	N/A
17-Sep-10	Tanah Merah	2367	7.36	2.35E+08	2.15E+08
	Pasir Mas	2103	6.38	N/A	N/A
	Kota Bharu	N/A	-1.45	N/A	N/A
	Groundwater	8607	30.61	N/A	N/A
2-Oct-10	Tanah Merah	4422	15.02	1.86E+08	2.41E+08
	Pasir Mas	2341	7.27	N/A	N/A
	Kota Bharu	N/A	-1.45	N/A	N/A
	Groundwater	7378	26.03	N/A	N/A
16-Oct-10	Tanah Merah	4167	14.07	N/A	N/A
	Pasir Mas	2262	6.97	N/A	N/A
	Kota Bharu	N/A	-1.45	N/A	N/A
	Groundwater	6666	23.38	N/A	N/A

Date	*Location*	*[CO_2] (ppmv)*	*CO_2 Evasion (g C day^{-1} m^{-2})*	*DOC Flux (g C day^{-1})*	*DIC Flux (g C day^{-1})*
8-Jan-11	Tanah Merah	3313	10.89	4.12E+08	7.10E+08
	Pasir Mas	3416	11.27	N/A	N/A
	Kota Bharu	3504	11.60	N/A	N/A
	Groundwater	11794	42.48	N/A	N/A
22-Jan-11	Tanah Merah	3460	11.43	8.10E+07	9.08E+07
	Pasir Mas	3401	11.22	N/A	N/A
	Kota Bharu	3408	11.24	N/A	N/A
	Groundwater	14711	53.34	N/A	N/A
8-Feb-11	Tanah Merah	3482	11.52	8.08E+07	1.30E+08
	Pasir Mas	3394	11.19	N/A	N/A
	Kota Bharu	3408	11.24	N/A	N/A
	Groundwater	13861	50.18	N/A	N/A
22-Feb-11	Tanah Merah	3430	11.33	3.88E+07	7.06E+07
	Pasir Mas	3570	11.84	N/A	N/A
	Kota Bharu	3533	11.71	N/A	N/A
	Groundwater	14096	51.05	N/A	N/A
5-Mar-11	Tanah Merah	3474	11.49	2.87E+07	5.84E+07
	Pasir Mas	3335	10.97	N/A	N/A
	Kota Bharu	5651	19.60	N/A	N/A
	Groundwater	15730	57.14	N/A	N/A
19-Mar-11	Tanah Merah	3474	11.49	6.28E+07	1.13E+08
	Pasir Mas	3438	11.35	N/A	N/A
	Kota Bharu	3562	11.82	N/A	N/A
	Groundwater	13561	49.06	N/A	N/A
2-Apr-11	Tanah Merah	6011	20.94	1.30E+08	3.34E+08
	Pasir Mas	5989	20.85	N/A	N/A
	Kota Bharu	6546	22.93	N/A	N/A
	Groundwater	11090	39.86	N/A	N/A
16-Apr-11	Tanah Merah	5695	19.76	1.15E+08	1.40E+08
	Pasir Mas	6458	22.60	N/A	N/A
	Kota Bharu	6516	22.82	N/A	N/A
	Groundwater	9910	35.46	N/A	N/A
7-May-11	Tanah Merah	6355	22.22	N/A	N/A
	Pasir Mas	5820	20.23	N/A	N/A
	Kota Bharu	6436	22.52	N/A	N/A
	Groundwater	10313	36.96	N/A	N/A
21-May-11	Tanah Merah	5915	20.58	N/A	N/A
	Pasir Mas	6165	21.51	N/A	N/A
	Kota Bharu	6055	21.10	N/A	N/A
	Groundwater	12073	43.52	N/A	N/A
4-Jun-11	Tanah Merah	6106	21.29	N/A	N/A
	Pasir Mas	6047	21.07	N/A	N/A
	Kota Bharu	6231	21.75	N/A	N/A
	Groundwater	10115	36.23	N/A	N/A
18-Jun-11	Tanah Merah	5754	19.98	N/A	N/A
	Pasir Mas	6384	22.33	N/A	N/A
	Kota Bharu	5857	20.36	N/A	N/A
	Groundwater	9939	35.57	N/A	N/A

Date	*Location*	*[CO_2]* (ppmv)	*CO_2 Evasion* (g C day^{-1} m^{-2})	*DOC Flux* (g C day^{-1})	*DIC Flux* (g C day^{-1})
2-Jul-11	Tanah Merah	9316	33.25	4.92E+07	1.63E+08
	Pasir Mas	10599	38.03	N/A	N/A
	Kota Bharu	20385	74.48	N/A	N/A
	Groundwater	10042	35.95	N/A	N/A
16-Jul-11	Tanah Merah	2228	6.85	5.63E+07	5.82E+07
	Pasir Mas	2250	6.93	N/A	N/A
	Kota Bharu	19791	72.26	N/A	N/A
	Groundwater	N/A	-1.45	N/A	N/A
6-Aug-11	Tanah Merah	2272	7.01	2.74E+07	3.22E+07
	Pasir Mas	902	1.91	N/A	N/A
	Kota Bharu	2272	7.01	N/A	N/A
	Groundwater	N/A	-1.45	N/A	N/A
20-Aug-11	Tanah Merah	850	1.71	4.07E+07	1.11E+07
	Pasir Mas	2829	9.09	N/A	N/A
	Kota Bharu	704	1.17	N/A	N/A
	Groundwater	N/A	-1.45	N/A	N/A
3-Sep-11	Tanah Merah	2177	6.66	3.20E+07	3.55E+07
	Pasir Mas	2170	6.63	N/A	N/A
	Kota Bharu	2199	6.74	N/A	N/A
	Groundwater	N/A	-1.45	N/A	N/A
17-Sep-11	Tanah Merah	2258	6.96	6.25E+07	7.08E+07
	Pasir Mas	19087	69.64	N/A	N/A
	Kota Bharu	2140	6.52	N/A	N/A
	Groundwater	2192	6.71	N/A	N/A

Appendix 9: Langat Basin PCA results from Pangsun and Kajang

Parameters	Pangsun				Kajang					
	VF1	VF2	VF3	VF4	VF1	VF2	VF3	VF4	VF5	VF6
$\delta^{13}C_{DOC}$	-0.11	0.09	0.07	-0.01	-0.18	-0.01	0.14	0.09	0.08	**0.95**
$\delta^{13}C_{DIC}$	-0.21	-0.36	-0.12	0.15	-0.12	-0.44	-0.19	-0.49	0.44	0.18
[DOC]	0.06	0.01	0.03	**0.98**	-0.13	0.02	-0.02	-0.06	**0.98**	0.06
[DIC]	-0.03	0.35	0.19	-0.10	0.1	**0.66**	0.51	0.28	0.05	0.08
[Ca]	**0.77**	0.32	0.35	0.10	**0.95**	0.01	-0.02	0.13	0.04	-0.10
[Cl]	0.18	0.04	**0.96**	0.01	-0.04	**0.95**	0.03	-0.05	0.03	0.04
[Fe]	0.33	**0.87**	0.08	-0.03	0.13	-0.25	**0.92**	-0.05	-0.15	0.07
[K]	**0.90**	0.04	0.02	0.31	0.27	**0.9**	-0.16	-0.13	-0.05	-0.09
[Mg]	**0.94**	0.21	-0.02	-0.03	0.07	0.23	**0.91**	0.01	0.1	0.10
[Mn]	0.40	**0.80**	0.17	0.12	**0.97**	0.06	0.13	0.04	-0.03	0.03
[Na]	**0.85**	0.39	0.22	-0.04	**0.96**	0.03	0.03	0.17	-0.11	-0.10
[NO3]	N/A	N/A	N/A	N/A	**0.56**	-0.30	-0.01	-0.50	0.13	0.09
[Si]	**0.91**	0.16	0.00	-0.09	**0.94**	0.15	0.13	-0.14	-0.18	-0.05
[SO4]	0.38	0.13	0.48	0.32	0.38	0.03	0.07	0.17	0.05	-0.07
[Sr]	**0.88**	0.35	0.21	0.00	**0.98**	0.02	0.00	0.03	-0.02	-0.10
[Zn]	0.28	**0.90**	-0.09	-0.02	0.17	-0.16	-0.04	**0.91**	-0.04	0.15
EC	-0.34	-0.20	0.07	0.09	0.03	0.08	-0.02	-0.13	-0.09	-0.09
pH	-0.17	-0.09	0.01	0.03	-0.18	0.08	-0.17	-0.23	0.07	0.09
TDS	-0.12	0.01	-0.12	0.07	-0.35	0.24	-0.02	-0.06	0.08	0.00
Temp	-0.31	-0.25	-0.09	0.04	-0.22	0.48	0.31	0.05	-0.02	0.26
Variance Explained	29%	16%	8%	7%	27%	15%	11%	8%	6%	6%

Appendix 10: Langat Basin PCA results from Dengkil and Semenyih

Parameters	Dengkil					Semenyih				
	VF1	VF2	VF3	VF4	VF5	VF1	VF2	VF3	VF4	VF5
$\delta^{13}C_{DOC}$	-0.22	-0.09	0.1	**0.95**	0.1	-0.23	-0.04	-0.01	**0.95**	0
$\delta^{13}C_{DIC}$	-0.23	0.06	0.14	0.09	**0.94**	-0.22	**0.52**	**0.57**	0.16	-0.34
[DOC]	-0.3	-0.02	0.16	**0.50**	-0.07	-0.16	-0.16	**0.93**	-0.03	-0.02
[DIC]	**0.68**	-0.01	-0.07	-0.01	-0.45	-0.13	-0.06	-0.07	0.01	**0.89**
[Ca]	**0.97**	0.05	-0.1	-0.09	-0.09	**0.88**	0.07	-0.01	-0.02	0.12
[Cl]	0.05	**0.97**	-0.04	-0.08	0.04	0.09	**0.95**	-0.04	0.05	0.05
[Fe]	-0.28	-0.08	**0.78**	0.27	0	-0.14	-0.02	-0.2	-0.02	-0.11
[K]	0.18	**0.93**	-0.07	-0.03	0.02	0.34	**0.89**	-0.09	-0.09	-0.1
[Mg]	-0.07	-0.06	**0.94**	0	0.16	-0.22	-0.1	-0.09	0.08	0.02
Mn	**0.97**	0.03	-0.06	-0.15	-0.07	**0.96**	0.11	-0.04	-0.07	0
[Na]	**0.95**	0.14	0	-0.09	-0.06	**0.95**	0.03	-0.07	-0.08	-0.09
[NO_3]	**0.74**	0.13	-0.08	0.01	-0.24	0.01	0.12	-0.14	-0.01	0.3
[Si]	**0.71**	0.14	-0.1	-0.18	-0.05	**0.95**	0.06	-0.12	-0.1	-0.07
[SO4]	**0.83**	-0.13	-0.12	-0.02	-0.11	0.1	-0.16	0.07	-0.01	0.01
[Sr]	**0.97**	0.09	-0.1	-0.13	-0.04	**0.97**	0.1	-0.05	-0.08	-0.06
[Zn]	0.02	-0.19	0.13	-0.08	0.13	0	-0.25	-0.07	-0.06	0.18
EC	-0.42	0.16	0.06	-0.05	0.09	-0.22	0.39	0.03	-0.16	-0.03
pH	-0.1	0.15	-0.12	-0.04	0.01	-0.22	0.06	-0.06	0.16	0.1
TDS	-0.02	0.09	-0.03	-0.02	-0.02	-0.02	0.55	-0.2	-0.33	-0.09
Temperature	0.29	-0.18	-0.03	0.01	-0.08	-0.02	-0.02	-0.04	0.05	0.15
Variance Explained	32%	10%	8%	7%	6%	24%	13%	7%	6%	6%

Appendix 11: Charge balance errors for all complete Dengkil Sub-basin cation/anion datasets

Sampling Date	**Charge Balance Error (%)**				
	Pangsun	**Kajang**	**Dengkil**	**Semenyih**	**Groundwater**
16-May-10	N/A	N/A	N/A	N/A	N/A
30-May-10	N/A	N/A	N/A	N/A	N/A
15-Jun-10	N/A	N/A	N/A	N/A	N/A
29-Jun-10	N/A	N/A	N/A	N/A	N/A
11-Jul-10	N/A	N/A	N/A	N/A	N/A
25-Jul-10	N/A	N/A	N/A	N/A	N/A
8-Aug-10	N/A	N/A	N/A	N/A	N/A
21-Aug-10	N/A	N/A	N/A	N/A	N/A
7-Sep-10	N/A	N/A	N/A	N/A	N/A
25-Sep-10	N/A	N/A	N/A	N/A	N/A
17-Oct-10	38.9	22.0	4.2	10.4	N/A
31-Oct-10	N/A	30.7	12.9	10.9	N/A
15-Nov-10	34.3	3.3	4.9	5.2	N/A
30-Nov-10	N/A	1.0	17.1	13.9	N/A
5-Dec-10	N/A	26.3	2.0	9.9	N/A
19-Dec-10	38.5	N/A	9.8	10.2	N/A
9-Jan-11	N/A	N/A	8.7	10.2	N/A
22-Jan-11	53.2	N/A	3.5	4.2	N/A
12-Feb-11	30.5	6.2	14.4	3.3	N/A
26-Feb-11	N/A	3.4	5.7	13.1	N/A
13-Mar-11	N/A	12.7	3.8	7.3	N/A
27-Mar-11	23.8	7.2	6.5	4.6	29.9
10-Apr-11	N/A	9.8	7.0	21.9	N/A
24-Apr-11	73.8	N/A	25.8	31.3	N/A
7-May-11	N/A	N/A	N/A	N/A	N/A
21-May-11	N/A	86.7	37.8	N/A	N/A
12-Jun-11	N/A	29.3	26.5	55.8	N/A
26-Jun-11	N/A	11.2	33.6	40.6	N/A
16-Jul-11	N/A	36.1	30.8	54.2	N/A
30-Jul-11	N/A	N/A	52.6	63.1	N/A
18-Aug-11	N/A	35.6	35.8	40.6	69.8
26-Aug-11	N/A	31.0	44.6	44.3	N/A
13-Sep-11	65.7	31.4	18.1	29.3	71.4
30-Sep-11	N/A	32.1	14.6	31.7	N/A
16-Oct-11	N/A	27.1	12.1	28.2	73.3
29-Oct-11	5.6	N/A	19.5	N/A	N/A
12-Nov-11	69.5	24.2	19.5	38.2	N/A
26-Nov-11	59.6	N/A	15.6	39.8	N/A
17-Dec-11	59.8	31.3	25.7	37.8	N/A
31-Dec-11	55.6	N/A	3.5	N/A	35.1

Appendix 12: Charge balance errors for all complete Kelantan Basin cation/anion datasets

Sampling Date	Charge Balance Error (%)			
	Tanah Merah	**Pasir Mas**	**Kota Bharu**	**Groundwater**
25-May-10	N/A	N/A	N/A	N/A
12-Jun-10	N/A	N/A	N/A	N/A
26-Jun-10	N/A	N/A	N/A	N/A
10-Jul-10	N/A	N/A	N/A	N/A
24-Jul-10	N/A	N/A	N/A	N/A
8-Aug-10	N/A	N/A	N/A	N/A
21-Aug-10	N/A	N/A	N/A	N/A
3-Sep-10	N/A	N/A	N/A	64.6
17-Sep-10	N/A	N/A	N/A	N/A
2-Oct-10	N/A	N/A	N/A	N/A
16-Oct-10	N/A	N/A	N/A	4.7
8-Jan-11	64.7	63.8	62.7	3.5
22-Jan-11	63.4	N/A	63.7	12.3
8-Feb-11	N/A	N/A	54.0	N/A
22-Feb-11	63.6	62.6	63.0	N/A
5-Mar-11	62.9	64.3	48.6	15.0
19-Mar-11	63.0	62.7	N/A	13.5
2-Apr-11	34.4	34.4	N/A	2.8
16-Apr-11	35.7	32.5	N/A	1.2
7-May-11	N/A	N/A	N/A	0.2
21-May-11	34.4	33.1	34.1	4.7
4-Jun-11	N/A	N/A	35.7	17.0
18-Jun-11	39.9	21.0	24.6	N/A
2-Jul-11	6.4	0.7	16.9	3.6
16-Jul-11	65.6	65.5	27.9	11.5
6-Aug-11	48.9	71.9	55.3	60.8
20-Aug-11	79.7	49.0	N/A	71.0
3-Sep-11	49.8	57.1	55.4	53.3
17-Sep-11	55.8	16.1	N/A	32.5

Appendix 13: Complete precipitation (NOAA database) and river flow rate (Malaysian DOE) data for selected locations in the Langat and Kelantan Basins, from May 2010 to December 2011.

Date	Flow Rates (m^3/s)		Precipitation (mm)	
	Langat River (Dengkil)	Kelantan River (Tanah Merah)	Langat Basin (Kuala Lumpur Airport)	Kelantan Basin (Kota Bharu)
1-May-10	47.37	98.80	23.62	0.00
2-May-10	42.88	97.50	16.76	0.00
3-May-10	43.63	98.50	6.10	0.00
4-May-10	19.86	99.70	0.00	0.00
5-May-10	22.77	100.00	12.70	0.00
6-May-10	45.77	98.80	44.70	0.00
7-May-10	17.38	98.20	11.43	0.00
8-May-10	16.56	98.00	0.00	0.00
9-May-10	18.92	97.50	33.02	2.54
10-May-10	31.52	98.10	0.76	0.00
11-May-10	26.78	99.60	23.88	0.00
12-May-10	41.23	97.20	21.84	0.00
13-May-10	109.58	97.50	0.00	13.97
14-May-10	160.46	97.10	2.54	0.00
15-May-10	96.06	96.70	13.46	4.83
16-May-10	41.91	96.30	0.00	0.51
17-May-10	36.1	95.80	16.76	3.30
18-May-10	103.63	94.50	1.52	0.51
19-May-10	34.24	96.20	28.19	51.31
20-May-10	24.96	127.70	1.02	2.54
21-May-10	90.64	111.00	37.59	0.00
22-May-10	46.09	96.20	0.00	0.00
23-May-10	144.65	97.20	6.35	8.38
24-May-10	54.17	98.00	0.00	0.00
25-May-10	220.68	100.30	0.00	64.77
26-May-10	54.71	103.30	0.00	23.62
27-May-10	38.81	105.40	0.00	0.00
28-May-10	27.92	108.10	0.00	0.00
29-May-10	24.31	110.30	44.70	0.00
30-May-10	21.31	112.60	70.36	0.00
31-May-10	20.29	114.90	0.51	0.00
1-Jun-10	26.63	117.40	20.57	0.51
2-Jun-10	16.83	117.30	16.51	0.00
3-Jun-10	37.21	120.10	0.00	0.00
4-Jun-10	36.69	122.90	30.73	0.00
5-Jun-10	75.52	124.70	9.91	4.32
6-Jun-10	55.20	137.70	0.00	0.25
7-Jun-10	25.42	147.20	0.00	0.25
8-Jun-10	25.92	149.50	0.76	15.75
9-Jun-10	22.52	152.10	6.10	0.00
10-Jun-10	19.93	153.90	45.21	0.51
11-Jun-10	19.44	157.60	0.00	1.02
12-Jun-10	56.07	161.30	7.62	0.51
13-Jun-10	28.22	163.60	5.84	0.00
14-Jun-10	33.65	165.60	0.00	0.00
15-Jun-10	35.46	168.00	0.00	0.00
16-Jun-10	76.54	170.90	0.00	0.25
17-Jun-10	33.21	177.50	0.00	48.01
18-Jun-10	21.77	183.70	0.00	51.56
19-Jun-10	21.45	157.70	0.00	0.51
20-Jun-10	16.28	144.50	0.00	0.00
21-Jun-10	15.15	147.10	0.51	0.00
22-Jun-10	14.50	149.90	2.03	4.83
23-Jun-10	14.21	152.50	0.00	0.51
24-Jun-10	18.48	160.60	19.30	4.83
25-Jun-10	15.32	200.20	1.52	0.00
26-Jun-10	20.21	191.10	18.54	5.84
27-Jun-10	18.70	190.00	0.76	0.00

Date	Flow Rates (m^3/s)		Precipitation (mm)	
	Langat River (Dengkil)	**Kelantan River (Tanah Merah)**	**Langat Basin (Kuala Lumpur Airport)**	**Kelantan Basin (Kota Bharu)**
28-Jun-10	15.50	195.20	0.00	0.00
29-Jun-10	14.52	271.20	0.00	0.00
30-Jun-10	42.46	243.00	4.06	0.00
1-Jul-10	28.03	320.50	0.00	0.51
2-Jul-10	29.27	545.40	74.42	92.71
3-Jul-10	N/A	410.40	1.52	1.78
4-Jul-10	18.55	235.50	0.00	0.00
5-Jul-10	N/A	156.20	10.41	0.00
6-Jul-10	122.15	125.30	0.00	0.00
7-Jul-10	115.93	120.00	0.00	0.00
8-Jul-10	39.07	119.80	9.91	1.27
9-Jul-10	24.71	122.70	0.00	0.00
10-Jul-10	21.92	146.20	0.25	0.51
11-Jul-10	17.66	162.40	3.56	0.00
12-Jul-10	63.00	191.10	1.27	0.00
13-Jul-10	100.71	274.40	0.00	0.00
14-Jul-10	28.35	225.60	0.00	10.41
15-Jul-10	30.40	185.50	0.00	0.00
16-Jul-10	30.25	174.70	11.68	0.00
17-Jul-10	22.45	207.30	4.32	0.00
18-Jul-10	19.03	186.70	0.00	49.53
19-Jul-10	27.77	202.30	5.08	22.86
20-Jul-10	54.38	184.10	0.00	0.00
21-Jul-10	22.90	166.20	70.87	6.35
22-Jul-10	37.75	165.70	0.51	0.00
23-Jul-10	22.16	177.30	0.00	14.48
24-Jul-10	39.93	206.40	0.00	12.70
25-Jul-10	22.08	184.70	0.00	3.30
26-Jul-10	N/A	145.50	17.78	0.00
27-Jul-10	N/A	147.10	0.00	0.00
28-Jul-10	N/A	129.90	16.00	24.89
29-Jul-10	N/A	115.20	0.00	0.51
30-Jul-10	N/A	115.20	0.00	59.18
31-Jul-10	N/A	115.80	0.00	0.25
1-Aug-10	N/A	168.80	18.80	7.11
2-Aug-10	N/A	178.50	0.00	27.69
3-Aug-10	43.59	132.30	0.76	0.76
4-Aug-10	23.18	174.00	0.00	2.54
5-Aug-10	23.42	264.70	0.00	7.87
6-Aug-10	21.72	325.90	2.29	0.00
7-Aug-10	15.77	353.10	0.00	0.00
8-Aug-10	13.53	353.10	0.00	0.00
9-Aug-10	60.24	350.80	1.02	1.02
10-Aug-10	25.22	350.50	0.00	0.00
11-Aug-10	17.52	350.50	0.00	0.00
12-Aug-10	22.14	266.00	0.00	0.25
13-Aug-10	24.04	152.20	0.00	0.00
14-Aug-10	18.22	152.30	75.69	0.00
15-Aug-10	14.95	207.60	0.76	0.00
16-Aug-10	13.41	276.40	5.84	0.00
17-Aug-10	13.54	262.80	24.38	0.00
18-Aug-10	19.13	213.70	39.88	2.54
19-Aug-10	69.19	236.20	6.10	3.30
20-Aug-10	37.59	285.40	0.76	1.02
21-Aug-10	40.56	263.10	0.00	37.34
22-Aug-10	217.24	196.90	0.00	0.00
23-Aug-10	123.92	159.20	0.00	2.29
24-Aug-10	259.50	142.80	0.00	1.52
25-Aug-10	111.06	141.00	0.00	0.00
26-Aug-10	52.32	139.10	0.00	0.51
27-Aug-10	38.54	158.70	0.25	0.51
28-Aug-10	32.29	159.70	0.25	0.00

Date	Flow Rates (m^3/s)		Precipitation (mm)	
	Langat River (Dengkil)	Kelantan River (Tanah Merah)	Langat Basin (Kuala Lumpur Airport)	Kelantan Basin (Kota Bharu)
29-Aug-10	30.06	148.20	0.00	0.00
30-Aug-10	25.60	146.00	0.00	1.02
31-Aug-10	22.63	187.00	2.79	0.25
1-Sep-10	23.83	264.60	29.21	2.03
2-Sep-10	60.01	235.40	0.00	0.51
3-Sep-10	N/A	192.10	5.84	0.00
4-Sep-10	N/A	175.20	0.51	6.60
5-Sep-10	39.67	236.70	6.10	0.25
6-Sep-10	24.98	336.00	1.27	7.11
7-Sep-10	38.72	259.60	2.79	3.05
8-Sep-10	N/A	209.50	1.02	22.10
9-Sep-10	N/A	193.00	38.86	3.56
10-Sep-10	N/A	207.80	5.08	1.52
11-Sep-10	N/A	181.30	10.67	0.00
12-Sep-10	N/A	170.90	1.52	0.25
13-Sep-10	N/A	199.40	0.25	0.00
14-Sep-10	N/A	255.40	9.91	22.86
15-Sep-10	N/A	307.20	0.51	26.67
16-Sep-10	N/A	443.00	0.00	5.59
17-Sep-10	N/A	461.80	16.51	0.00
18-Sep-10	N/A	493.10	8.38	0.51
19-Sep-10	N/A	325.60	4.83	0.51
20-Sep-10	N/A	235.60	0.00	0.25
21-Sep-10	N/A	251.30	1.52	0.00
22-Sep-10	N/A	292.90	45.21	0.00
23-Sep-10	N/A	271.80	6.10	0.00
24-Sep-10	N/A	253.60	0.00	0.00
25-Sep-10	N/A	231.40	6.10	0.25
26-Sep-10	N/A	180.60	8.89	24.64
27-Sep-10	N/A	171.30	5.59	0.25
28-Sep-10	N/A	190.50	41.91	13.97
29-Sep-10	N/A	246.20	2.03	0.25
30-Sep-10	N/A	254.50	47.50	0.00
1-Oct-10	N/A	258.10	10.67	0.00
2-Oct-10	N/A	277.40	1.02	14.73
3-Oct-10	N/A	256.80	13.72	0.00
4-Oct-10	N/A	251.60	7.87	8.13
5-Oct-10	N/A	267.90	0.00	10.16
6-Oct-10	N/A	281.50	8.13	0.00
7-Oct-10	N/A	286.10	0.00	54.86
8-Oct-10	N/A	319.70	0.00	1.27
9-Oct-10	N/A	209.30	0.00	0.00
10-Oct-10	N/A	154.60	0.00	0.00
11-Oct-10	N/A	142.30	0.25	0.00
12-Oct-10	N/A	131.10	0.00	0.00
13-Oct-10	N/A	N/A	0.00	1.27
14-Oct-10	N/A	N/A	0.00	5.33
15-Oct-10	N/A	N/A	0.00	5.33
16-Oct-10	N/A	N/A	0.00	0.25
17-Oct-10	N/A	N/A	0.00	0.25
18-Oct-10	N/A	N/A	13.97	0.00
19-Oct-10	N/A	N/A	0.00	7.11
20-Oct-10	N/A	N/A	0.00	0.00
21-Oct-10	N/A	N/A	0.00	0.00
22-Oct-10	N/A	N/A	0.00	0.00
23-Oct-10	N/A	N/A	0.00	0.00
24-Oct-10	N/A	N/A	2.03	0.00
25-Oct-10	N/A	N/A	1.02	26.67
26-Oct-10	N/A	N/A	0.51	0.00
27-Oct-10	N/A	N/A	0.00	0.00
28-Oct-10	N/A	N/A	0.00	0.00
29-Oct-10	N/A	N/A	79.50	27.43

Date	Flow Rates (m^3/s)		Precipitation (mm)	
	Langat River (Dengkil)	Kelantan River (Tanah Merah)	Langat Basin (Kuala Lumpur Airport)	Kelantan Basin (Kota Bharu)
30-Oct-10	N/A	N/A	14.48	11.68
31-Oct-10	N/A	N/A	4.32	1.27
1-Nov-10	N/A	N/A	2.29	161.04
2-Nov-10	99.53	N/A	0.00	45.21
3-Nov-10	192.47	N/A	0.00	52.83
4-Nov-10	N/A	N/A	0.00	0.76
5-Nov-10	N/A	N/A	0.00	50.29
6-Nov-10	N/A	N/A	0.00	0.25
7-Nov-10	N/A	N/A	1.52	0.51
8-Nov-10	N/A	N/A	0.00	3.56
9-Nov-10	N/A	N/A	0.51	28.19
10-Nov-10	N/A	N/A	0.00	8.13
11-Nov-10	N/A	N/A	0.00	1.02
12-Nov-10	N/A	N/A	5.33	18.54
13-Nov-10	N/A	N/A	0.25	0.00
14-Nov-10	N/A	N/A	0.51	34.54
15-Nov-10	N/A	N/A	10.92	23.11
16-Nov-10	N/A	N/A	50.55	3.30
17-Nov-10	N/A	N/A	25.91	30.48
18-Nov-10	N/A	N/A	0.00	0.00
19-Nov-10	N/A	N/A	4.57	0.00
20-Nov-10	N/A	N/A	27.18	23.11
21-Nov-10	N/A	N/A	0.00	10.67
22-Nov-10	N/A	N/A	0.76	23.11
23-Nov-10	118.68	N/A	0.00	0.00
24-Nov-10	44.43	N/A	46.48	14.48
25-Nov-10	31.38	N/A	0.51	0.25
26-Nov-10	32.32	N/A	2.54	0.51
27-Nov-10	45	N/A	15.24	1.78
28-Nov-10	50.47	N/A	42.42	228.85
29-Nov-10	117.90	N/A	9.14	1.27
30-Nov-10	54.28	N/A	2.03	10.92
1-Dec-10	106.15	N/A	1.78	30.48
2-Dec-10	32.67	N/A	59.18	105.41
3-Dec-10	29.24	N/A	1.52	35.05
4-Dec-10	140.23	N/A	0.00	24.89
5-Dec-10	79.62	N/A	0.51	35.05
6-Dec-10	52.52	N/A	0.00	16.76
7-Dec-10	40.39	N/A	0.76	75.69
8-Dec-10	62.97	N/A	0.00	14.99
9-Dec-10	42.09	N/A	23.11	0.00
10-Dec-10	55.39	N/A	0.00	2.29
11-Dec-10	58.99	N/A	0.00	11.68
12-Dec-10	107.94	N/A	0.00	0.00
13-Dec-10	40.44	N/A	0.00	0.00
14-Dec-10	31.77	N/A	0.76	0.00
15-Dec-10	27.71	N/A	0.00	0.25
16-Dec-10	26.22	N/A	0.51	0.00
17-Dec-10	26.77	N/A	5.84	12.19
18-Dec-10	24.11	N/A	8.64	44.45
19-Dec-10	24.37	N/A	0.00	51.56
20-Dec-10	30.87	N/A	3.81	2.29
21-Dec-10	35.24	N/A	91.44	17.53
22-Dec-10	27.66	N/A	0.00	44.45
23-Dec-10	26.30	N/A	36.32	5.59
24-Dec-10	34.00	N/A	1.02	15.49
25-Dec-10	49.06	N/A	2.29	0.00
26-Dec-10	81.90	N/A	0.00	0.00
27-Dec-10	51.87	N/A	0.00	0.51
28-Dec-10	92.70	223.70	0.00	7.87
29-Dec-10	61.35	653.10	5.59	75.95
30-Dec-10	37.80	1781.80	0.76	7.87

Date	Flow Rates (m^3/s)		Precipitation (mm)	
	Langat River (Dengkil)	Kelantan River (Tanah Merah)	Langat Basin (Kuala Lumpur Airport)	Kelantan Basin (Kota Bharu)
31-Dec-10	26.93	2339.80	0.00	105.66
1-Jan-11	20.20	1587.70	0.00	3.30
2-Jan-11	19.63	876.40	18.54	0.25
3-Jan-11	24.75	1171.60	0.00	10.16
4-Jan-11	114.70	1083.30	6.60	0.00
5-Jan-11	185.25	1181.70	28.45	7.37
6-Jan-11	75.96	1830.50	7.87	97.79
7-Jan-11	38.74	2169.70	3.30	186.18
8-Jan-11	26.11	1818.30	0.00	39.88
9-Jan-11	20.57	1295.60	0.00	2.03
10-Jan-11	25.53	867.90	0.00	3.30
11-Jan-11	27.84	748.70	3.05	0.51
12-Jan-11	20.43	622.60	0.00	0.00
13-Jan-11	71.42	545.40	0.25	0.00
14-Jan-11	93.61	486.80	10.67	0.00
15-Jan-11	47.08	449.50	6.86	0.00
16-Jan-11	45.62	437.80	0.00	0.00
17-Jan-11	26.36	347.50	0.00	0.00
18-Jan-11	31.05	287.70	0.00	0.00
19-Jan-11	36.33	267.80	0.00	0.00
20-Jan-11	22.58	252.80	0.00	0.00
21-Jan-11	32.26	235.00	0.00	0.00
22-Jan-11	24.92	222.60	0.00	0.25
23-Jan-11	21.09	235.70	0.00	0.00
24-Jan-11	27.62	225.90	17.53	10.41
25-Jan-11	20.68	239.20	4.32	1.52
26-Jan-11	17.10	312.10	13.21	0.00
27-Jan-11	18.11	614.90	0.00	3.30
28-Jan-11	16.86	1643.60	12.95	0.51
29-Jan-11	17.28	2046.00	0.00	2.54
30-Jan-11	55.75	1527.50	3.81	0.00
31-Jan-11	152.05	1306.10	42.93	3.30
1-Feb-11	43.57	1093.90	0.51	0.25
2-Feb-11	26.40	831.10	0.00	0.00
3-Feb-11	21.80	632.80	5.59	0.00
4-Feb-11	19.47	512.30	5.59	0.00
5-Feb-11	18.87	422.50	0.00	0.00
6-Feb-11	23.47	370.40	9.91	0.00
7-Feb-11	22.79	352.10	0.00	0.00
8-Feb-11	43.68	317.90	0.00	0.00
9-Feb-11	26.08	287.60	0.00	0.00
10-Feb-11	33.03	269.70	0.00	0.00
11-Feb-11	21.38	279.30	0.00	0.00
12-Feb-11	28.42	299.40	8.38	0.00
13-Feb-11	38.89	280.30	1.27	0.00
14-Feb-11	61.91	252.30	5.08	0.00
15-Feb-11	65.89	241.80	0.00	0.00
16-Feb-11	27.94	252.60	4.32	0.51
17-Feb-11	21.31	237.90	4.32	0.00
18-Feb-11	22.90	223.70	9.65	0.00
19-Feb-11	20.45	232.70	1.02	0.00
20-Feb-11	14.74	210.80	0.00	0.00
21-Feb-11	13.70	184.70	2.29	0.00
22-Feb-11	12.40	174.70	0.00	0.00
23-Feb-11	14.71	178.90	0.25	0.25
24-Feb-11	39.10	189.30	0.00	0.00
25-Feb-11	75.02	199.40	0.76	0.00
26-Feb-11	42.78	188.50	1.27	0.00
27-Feb-11	37.61	165.70	17.27	0.00
28-Feb-11	33.73	157.10	14.73	0.00
1-Mar-11	20.35	146.70	0.00	0.00
2-Mar-11	99.42	145.90	0.00	0.00

Date	Flow Rates (m^3/s)		Precipitation (mm)	
	Langat River (Dengkil)	**Kelantan River (Tanah Merah)**	**Langat Basin (Kuala Lumpur Airport)**	**Kelantan Basin (Kota Bharu)**
3-Mar-11	46.54	137.70	45.72	0.00
4-Mar-11	48.66	141.70	0.00	0.00
5-Mar-11	27.31	142.60	0.51	0.00
6-Mar-11	51.18	138.20	0.00	0.00
7-Mar-11	52.08	137.60	0.00	0.00
8-Mar-11	23.97	145.70	3.30	10.41
9-Mar-11	29.89	178.10	0.00	67.82
10-Mar-11	31.57	241.30	1.27	2.29
11-Mar-11	64.61	215.60	0.00	0.00
12-Mar-11	43.99	573.70	5.33	42.67
13-Mar-11	N/A	1318.00	18.29	76.96
14-Mar-11	N/A	532.80	23.62	10.92
15-Mar-11	N/A	310.50	19.81	11.43
16-Mar-11	N/A	246.00	12.95	1.78
17-Mar-11	N/A	238.70	0.00	0.25
18-Mar-11	25.51	326.70	23.11	0.00
19-Mar-11	20.54	275.40	7.11	0.25
20-Mar-11	23.51	238.50	1.02	0.51
21-Mar-11	31.16	259.30	55.12	8.89
22-Mar-11	39.28	301.10	12.70	0.00
23-Mar-11	55.83	291.20	7.11	31.50
24-Mar-11	62.28	288.90	24.13	12.70
25-Mar-11	109.56	291.60	39.37	115.32
26-Mar-11	107.32	436.10	0.00	4.32
27-Mar-11	52.41	345.50	0.00	34.29
28-Mar-11	56.86	256.40	0.00	9.91
29-Mar-11	36.21	640.70	0.00	119.38
30-Mar-11	26.98	1231.60	2.29	7.87
31-Mar-11	23.39	703.90	0.00	88.90
1-Apr-11	159.31	441.70	0.00	0.00
2-Apr-11	81.73	471.40	0.00	5.33
3-Apr-11	29.18	649.60	0.00	2.79
4-Apr-11	26.70	495.90	1.52	0.00
5-Apr-11	27.55	361.50	0.00	0.00
6-Apr-11	22.84	422.60	2.29	0.00
7-Apr-11	24.79	422.10	0.00	0.00
8-Apr-11	23.15	296.30	15.75	0.00
9-Apr-11	33.67	250.60	22.10	0.00
10-Apr-11	53.50	252.40	0.00	0.00
11-Apr-11	35.83	397.60	28.45	0.00
12-Apr-11	27.73	370.40	5.08	0.00
13-Apr-11	42.69	271.60	0.76	0.00
14-Apr-11	48.69	287.30	8.89	0.00
15-Apr-11	71.36	228.50	0.00	0.00
16-Apr-11	74.74	207.80	34.54	0.00
17-Apr-11	46.70	199.90	27.69	0.00
18-Apr-11	49.76	203.20	0.00	3.30
19-Apr-11	82.19	287.20	0.00	0.25
20-Apr-11	79.18	262.20	7.87	0.51
21-Apr-11	60.76	237.50	28.96	0.00
22-Apr-11	51.11	207.70	30.48	0.00
23-Apr-11	115.16	185.10	8.89	0.00
24-Apr-11	123.42	173.70	4.06	0.00
25-Apr-11	60.53	N/A	11.18	0.00
26-Apr-11	47.04	N/A	11.43	0.00
27-Apr-11	62.56	N/A	13.21	0.00
28-Apr-11	68.22	N/A	0.25	0.00
29-Apr-11	35.20	N/A	30.99	0.00
30-Apr-11	152.30	N/A	2.03	0.00
1-May-11	189.74	N/A	1.78	0.00
2-May-11	33.26	N/A	3.81	0.00
3-May-11	27.53	N/A	7.11	0.00

Date	Flow Rates (m^3/s)		Precipitation (mm)	
	Langat River (Dengkil)	Kelantan River (Tanah Merah)	Langat Basin (Kuala Lumpur Airport)	Kelantan Basin (Kota Bharu)
4-May-11	30.01	N/A	0.51	0.00
5-May-11	47.99	N/A	3.05	0.00
6-May-11	77.28	N/A	0.00	16.51
7-May-11	189.57	N/A	0.00	0.00
8-May-11	206.73	N/A	0.00	0.00
9-May-11	73.39	N/A	0.00	30.23
10-May-11	48.13	N/A	0.00	11.68
11-May-11	39.55	N/A	0.00	0.00
12-May-11	34.36	N/A	0.00	0.00
13-May-11	30.21	N/A	32.77	9.65
14-May-11	28.16	N/A	0.00	0.00
15-May-11	27.34	N/A	0.00	0.00
16-May-11	35.39	N/A	52.58	0.00
17-May-11	60.55	N/A	4.32	0.00
18-May-11	27.87	N/A	27.69	0.00
19-May-11	27.25	N/A	24.13	33.53
20-May-11	36.65	N/A	12.70	0.00
21-May-11	61.93	N/A	0.00	0.00
22-May-11	56.85	N/A	3.81	0.00
23-May-11	83.06	N/A	2.54	0.00
24-May-11	182.84	N/A	0.25	0.25
25-May-11	103.32	N/A	0.25	0.00
26-May-11	66.59	N/A	0.00	5.59
27-May-11	74.34	N/A	2.03	6.86
28-May-11	49.24	N/A	5.08	0.00
29-May-11	57.10	N/A	4.32	0.00
30-May-11	40.59	N/A	0.00	0.25
31-May-11	43.56	N/A	13.46	0.00
1-Jun-11	35.85	N/A	0.00	3.81
2-Jun-11	31.57	N/A	1.52	0.00
3-Jun-11	28.46	N/A	0.00	0.25
4-Jun-11	31.72	N/A	0.00	0.00
5-Jun-11	34.70	N/A	0.00	0.00
6-Jun-11	32.10	N/A	39.37	6.86
7-Jun-11	33.17	N/A	0.00	0.51
8-Jun-11	42.11	N/A	0.25	4.32
9-Jun-11	27.09	N/A	2.54	0.76
10-Jun-11	28.45	N/A	0.00	7.62
11-Jun-11	23.12	N/A	36.58	32.26
12-Jun-11	21.73	N/A	0.00	0.00
13-Jun-11	45.64	N/A	0.00	1.52
14-Jun-11	27.63	N/A	0.00	0.00
15-Jun-11	30.53	N/A	0.00	0.00
16-Jun-11	27.83	N/A	0.00	22.10
17-Jun-11	25.43	N/A	0.00	0.00
18-Jun-11	24.70	N/A	0.00	1.02
19-Jun-11	22.15	N/A	0.00	51.82
20-Jun-11	22.06	N/A	0.51	0.00
21-Jun-11	22.98	N/A	0.00	6.35
22-Jun-11	22.23	N/A	0.00	30.23
23-Jun-11	21.09	N/A	0.51	0.00
24-Jun-11	20.44	N/A	0.25	0.00
25-Jun-11	19.44	N/A	0.00	0.00
26-Jun-11	29.37	N/A	3.05	8.13
27-Jun-11	26.02	N/A	20.83	0.00
28-Jun-11	21.71	284.90	4.06	0.51
29-Jun-11	21.01	410.10	0.00	0.00
30-Jun-11	21.35	218.30	10.92	16.26
1-Jul-11	42.53	171.60	0.00	0.00
2-Jul-11	27.59	148.60	0.00	0.00
3-Jul-11	78.05	180.50	0.00	0.00
4-Jul-11	48.36	258.30	0.00	0.51

Date	Flow Rates (m^3/s)		Precipitation (mm)	
	Langat River (Dengkil)	**Kelantan River (Tanah Merah)**	**Langat Basin (Kuala Lumpur Airport)**	**Kelantan Basin (Kota Bharu)**
5-Jul-11	37.50	210.90	0.00	2.29
6-Jul-11	21.13	211.50	0.00	0.00
7-Jul-11	18.83	157.00	2.03	0.00
8-Jul-11	17.22	144.60	10.16	0.00
9-Jul-11	16.96	142.50	0.00	0.00
10-Jul-11	14.06	129.60	8.64	0.00
11-Jul-11	14.65	112.60	0.51	0.00
12-Jul-11	17.17	110.70	0.00	0.00
13-Jul-11	23.17	118.60	0.00	35.05
14-Jul-11	21.15	155.80	9.14	0.00
15-Jul-11	20.46	164.80	4.06	0.51
16-Jul-11	23.21	221.50	5.08	13.97
17-Jul-11	16.15	229.80	0.00	0.51
18-Jul-11	15.24	181.50	0.00	23.88
19-Jul-11	14.85	161.20	0.00	0.00
20-Jul-11	29.00	127.50	0.00	17.02
21-Jul-11	41.79	115.80	0.00	0.51
22-Jul-11	22.33	135.00	0.00	2.79
23-Jul-11	17.38	162.90	0.00	0.00
24-Jul-11	14.16	168.50	0.00	20.32
25-Jul-11	14.39	293.50	0.25	8.64
26-Jul-11	15.48	327.90	0.00	0.00
27-Jul-11	15.18	187.00	0.00	27.69
28-Jul-11	14.28	174.40	17.27	0.00
29-Jul-11	14.76	191.40	18.29	0.00
30-Jul-11	15.13	144.70	4.32	0.00
31-Jul-11	14.05	114.00	36.07	0.00
1-Aug-11	13.94	97.10	0.51	0.00
2-Aug-11	17.00	91.10	0.00	0.00
3-Aug-11	110.74	86.60	0.00	0.00
4-Aug-11	52.70	94.00	3.56	2.29
5-Aug-11	N/A	112.60	9.14	0.00
6-Aug-11	18.71	120.10	0.00	0.00
7-Aug-11	15.53	94.10	0.00	0.00
8-Aug-11	19.38	154.30	0.00	6.86
9-Aug-11	48.20	129.10	0.00	0.00
10-Aug-11	88.61	101.20	0.00	0.00
11-Aug-11	27.31	98.70	80.26	0.00
12-Aug-11	20.35	121.10	0.00	6.10
13-Aug-11	18.07	119.80	1.27	25.40
14-Aug-11	17.73	113.00	34.29	0.00
15-Aug-11	29.40	126.60	5.08	0.00
16-Aug-11	34.15	160.00	0.00	3.56
17-Aug-11	33.06	192.20	0.00	0.00
18-Aug-11	78.28	165.00	10.67	0.00
19-Aug-11	62.47	123.30	1.02	0.00
20-Aug-11	45.20	111.10	10.41	0.00
21-Aug-11	36.13	123.50	0.51	0.00
22-Aug-11	25.22	123.30	0.25	0.00
23-Aug-11	19.89	167.10	48.01	78.49
24-Aug-11	19.28	271.70	2.29	0.00
25-Aug-11	47.85	262.70	0.00	1.78
26-Aug-11	30.51	253.30	2.29	8.89
27-Aug-11	34.89	202.60	2.54	4.06
28-Aug-11	85.18	160.60	0.00	0.25
29-Aug-11	54.83	171.20	24.89	23.11
30-Aug-11	48.02	439.30	0.25	5.59
31-Aug-11	63.95	186.10	0.00	0.00
1-Sep-11	50.55	181.60	0.00	10.41
2-Sep-11	28.10	172.40	0.00	0.00
3-Sep-11	19.52	138.20	0.00	0.00
4-Sep-11	19.88	133.60	0.00	0.00

Date	Flow Rates (m^3/s)		Precipitation (mm)	
	Langat River (Dengkil)	Kelantan River (Tanah Merah)	Langat Basin (Kuala Lumpur Airport)	Kelantan Basin (Kota Bharu)
5-Sep-11	27.86	167.00	0.00	1.27
6-Sep-11	23.65	251.80	0.00	0.00
7-Sep-11	22.84	195.10	0.00	0.00
8-Sep-11	19.44	180.60	3.30	2.29
9-Sep-11	16.91	161.60	0.00	4.32
10-Sep-11	13.72	174.90	1.27	3.81
11-Sep-11	14.05	229.00	23.11	36.83
12-Sep-11	15.57	163.30	0.00	0.00
13-Sep-11	13.78	119.40	0.00	0.00
14-Sep-11	23.45	123.60	6.35	0.00
15-Sep-11	59.40	298.20	56.39	5.08
16-Sep-11	28.07	362.70	0.00	0.00
17-Sep-11	18.63	265.90	14.99	0.00
18-Sep-11	43.89	199.80	0.00	0.00
19-Sep-11	56.39	216.90	1.52	0.51
20-Sep-11	38.25	289.50	34.04	0.00
21-Sep-11	70.31	187.90	0.00	5.33
22-Sep-11	137.13	253.10	29.72	0.00
23-Sep-11	83.30	274.70	1.27	10.92
24-Sep-11	38.42	274.10	0.00	0.00
25-Sep-11	46.43	173.60	0.00	0.00
26-Sep-11	55.79	166.20	0.00	0.00
27-Sep-11	29.40	183.90	28.19	13.97
28-Sep-11	21.82	186.10	0.25	7.11
29-Sep-11	20.51	157.80	0.00	8.13
30-Sep-11	20.74	154.10	0.00	4.32
1-Oct-11	66.03	125.70	1.02	0.51
2-Oct-11	26.98	119.30	2.03	0.51
3-Oct-11	48.05	123.60	0.00	0.00
4-Oct-11	31.59	123.00	0.00	11.43
5-Oct-11	22.26	158.70	0.00	10.16
6-Oct-11	22.81	375.70	1.27	2.03
7-Oct-11	21.54	266.30	0.00	0.00
8-Oct-11	34.28	272.50	0.00	28.96
9-Oct-11	49.60	457.80	11.43	7.37
10-Oct-11	57.07	928.60	0.00	20.57
11-Oct-11	46.69	527.90	0.00	1.78
12-Oct-11	48.46	436.60	0.00	1.27
13-Oct-11	31.61	371.70	0.00	42.42
14-Oct-11	22.21	278.20	0.00	0.00
15-Oct-11	22.01	295.00	4.06	0.00
16-Oct-11	19.95	222.60	3.56	0.00
17-Oct-11	16.72	238.30	7.37	0.00
18-Oct-11	17.13	249.80	19.81	8.13
19-Oct-11	19.05	243.30	32.77	24.13
20-Oct-11	26.51	235.00	8.64	0.51
21-Oct-11	20.22	246.30	7.87	0.25
22-Oct-11	16.54	357.70	86.61	5.08
23-Oct-11	57.07	311.40	0.00	4.83
24-Oct-11	94.64	223.10	9.14	1.52
25-Oct-11	158.26	N/A	0.25	18.54
26-Oct-11	179.42	212.00	4.83	10.67
27-Oct-11	50.37	275.60	21.08	18.29
28-Oct-11	38.06	255.30	12.70	0.76
29-Oct-11	47.75	264.30	40.13	34.54
30-Oct-11	89.62	304.80	0.00	38.35
31-Oct-11	121.33	309.50	28.19	61.47
1-Nov-11	72.33	444.90	68.83	44.70
2-Nov-11	101.20	379.00	0.00	14.48
3-Nov-11	81.14	320.40	18.03	2.54
4-Nov-11	84.07	278.70	0.00	4.06
5-Nov-11	76.65	245.60	1.52	0.00

Date	Flow Rates (m^3/s)		Precipitation (mm)	
	Langat River (Dengkil)	**Kelantan River (Tanah Merah)**	**Langat Basin (Kuala Lumpur Airport)**	**Kelantan Basin (Kota Bharu)**
6-Nov-11	57.50	315.00	0.00	0.00
7-Nov-11	92.46	353.70	0.76	0.51
8-Nov-11	52.78	260.20	4.06	14.99
9-Nov-11	36.22	242.40	1.78	0.00
10-Nov-11	42.68	223.20	0.00	0.00
11-Nov-11	30.20	209.90	18.29	0.00
12-Nov-11	25.41	275.10	39.88	1.27
13-Nov-11	22.20	242.80	0.00	7.37
14-Nov-11	39.43	240.00	25.65	63.75
15-Nov-11	60.04	241.30	23.88	18.29
16-Nov-11	57.36	253.20	16.51	19.56
17-Nov-11	63.18	256.30	38.35	0.25
18-Nov-11	58.95	208.70	8.13	0.00
19-Nov-11	57.81	207.00	10.41	0.51
20-Nov-11	92.35	221.10	1.52	16.26
21-Nov-11	155.48	312.90	8.38	106.68
22-Nov-11	74.85	685.30	2.03	97.28
23-Nov-11	165.26	2297.90	34.80	184.91
24-Nov-11	130.95	4191.50	0.00	123.70
25-Nov-11	51.84	3711.30	0.25	10.67
26-Nov-11	75.46	2641.40	0.00	20.07
27-Nov-11	44.73	2155.20	2.79	0.00
28-Nov-11	32.96	N/A	12.70	1.52
29-Nov-11	32.94	N/A	0.76	1.02
30-Nov-11	43.77	N/A	7.37	0.00
1-Dec-11	84.54	N/A	28.70	1.02
2-Dec-11	N/A	N/A	17.02	8.89
3-Dec-11	N/A	N/A	9.91	0.25
4-Dec-11	49.34	N/A	0.00	2.79
5-Dec-11	128.07	N/A	35.31	27.69
6-Dec-11	319.87	N/A	0.00	0.00
7-Dec-11	123.99	N/A	0.00	0.00
8-Dec-11	115.19	N/A	6.10	0.00
9-Dec-11	51.01	N/A	12.70	0.00
10-Dec-11	38.74	N/A	0.00	4.32
11-Dec-11	63.07	N/A	0.00	4.83
12-Dec-11	N/A	N/A	5.33	118.87
13-Dec-11	N/A	N/A	0.00	11.43
14-Dec-11	N/A	N/A	0.25	11.68
15-Dec-11	N/A	N/A	0.00	4.32
16-Dec-11	N/A	N/A	0.00	155.96
17-Dec-11	N/A	N/A	0.51	7.62
18-Dec-11	N/A	N/A	26.16	0.76
19-Dec-11	N/A	N/A	0.00	14.99
20-Dec-11	N/A	N/A	32.51	7.11
21-Dec-11	N/A	N/A	9.14	12.19
22-Dec-11	N/A	N/A	0.51	11.68
23-Dec-11	N/A	N/A	2.03	0.51
24-Dec-11	N/A	N/A	18.80	0.00
25-Dec-11	N/A	N/A	7.62	1.02
26-Dec-11	N/A	N/A	0.00	0.00
27-Dec-11	N/A	N/A	0.00	0.00
28-Dec-11	N/A	N/A	6.86	5.33
29-Dec-11	N/A	N/A	0.00	0.00
30-Dec-11	N/A	N/A	0.00	5.08
31-Dec-11	N/A	N/A	1.27	21.59

Appendix 14: Abstract of Lee et al. (2013), *Aquatic Geochemistry* July 2013.

Abstract Langat River drains a tropical watershed in the southwest of the Malaysian Peninsula. The watershed is heavily urbanized in its downstream portion. Water samples were collected from May 2010 to December 2011, at three localities along the main stem river, 1 location at its Semenyih tributary and from an upstream groundwater source. Concentration and $\delta^{13}C$ data of riverine DIC and DOC indicate the dominance of C3 plant-derived material as the primary source of carbon, with $\delta^{13}C_{DIC}$ values enriched in ^{13}C relative to that of the C3 source. This enrichment is likely due to CO_2 outgassing, as calculated concentrations of riverine CO_2 are significantly higher than ambient atmospheric values, with methanogenic activity a theoretically possible contributing factor, particularly at the upstream location. The Langat River therefore acts as a net source of CO_2, with a total sub-basin flux of 19.7×10^3 t C year^{-1}. This is comparable to the sum of riverine DOC, DIC and POC loss rates from the sub-basin, calculated as 24.5×10^3 t C year^{-1}, and highlights the significance of CO_2 evasion from water bodies to the atmosphere for balancing the budget of the terrestrial carbon cycle. The DIC and DOC concentration and $\delta^{13}C$ data also suggests that in the more urbanized downriver areas, much of the organic carbon input may be anthropogenicaly derived due to ubiquity of sewage treatment plants and landfill sites. Such human-induced perturbations to riverine carbon cycling should be taken into account in future studies of urbanized watersheds.

Keywords Carbon cycle · Rivers · Stable isotopes · Carbon · Biogeochemistry · Environmental geology