to flashier hydrographs. Ploughing wet soils can cause impermeable smears in the subsoil called plough pans. These inhibit percolation leading to greater surface flows.
  - Terracing on hillsides stops movement of water downhill and subdues hydrographs.
  - Grass crops increase infiltration and lead to subdued hydrographs.
  - Large numbers of animals on small areas can impact soils leading to overland flows.
- Growth of urban areas and other large impermeable surfaces such as roads lead to flashy hydrographs (see Chapter 9). This is exacerbated by the very fact that settlements have been built on floodplains. This urban growth leads to the expansion of built-up, impermeable surfaces such as roads, car parks, shopping centres, etc. Most settlements are designed to transfer water as quickly as possible away from human activity to the nearest river. This is achieved through road camber, building design and drainage systems. In many cities in the UK there has been a continued loss of front gardens in favour of paved drives. Due to the growing number of two-/three-car families, an area of vegetated garden equivalent to 300 ha/year was lost in London between 1998 and 2006.

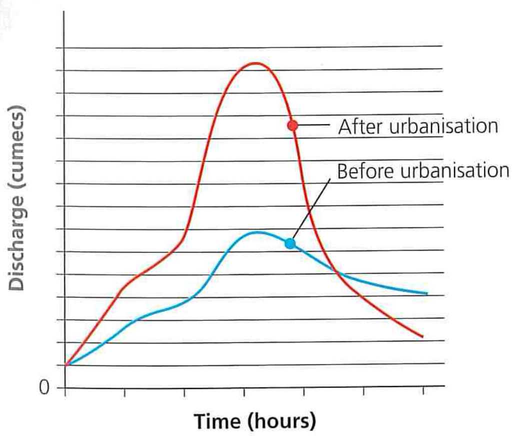

Figure 1.30 The influence of land use change on flood hydrographs: Impermeable surfaces shaped to get rid of water quickly, combined with a dense network of smooth drains, means that water gets to the river very quickly. The river itself can also be altered, for example, to move the water rapidly away from the urban area

Skills focus

You need to be able to draw storm hydrographs accurately and be able to label them with reasons for their pattern.

- Some soft engineering flood management schemes attempt to reduce flashiness in a river's hydrograph. Afforestation increases interception and infiltration. This slows down the progress of water to the river channel and subdues any changes in discharge.
- Water abstraction reduces the base flow and so more water must reach the channel before it reaches bankfull capacity.

Examples of how land use changes can affect the water cycle

Deforestation

Tropical South America contains the world's largest continuous tropical forest and savannah ecosystems. This region is environmentally important not only because of traditional ecological measures, such as its high biodiversity, but also because it generates more than a quarter of the world's river discharge. It has undergone explosive development and deforestation in the last 50 years as national and international demand for cattle feed (mostly soy), beef and sugar cane for ethanol, have increased. Already about 10 per cent of the rainforest in this large region has been converted to cattle pasture and agriculture.

Deforestation and forest degradation result in a complex set of changes to streams of all sizes. When forests are removed, the new vegetation generally has fewer leaves and shallower roots. This means it uses less water than the forest it replaces. The result is that less water evaporates from the land surface to be returned to the atmosphere; more water runs off of the land and stream flow is increased. The amount of change that occurs depends on local conditions including the amount of rainfall, how much of a watershed is deforested, topography, soils and the land use after deforestation. Studies have shown that there is little effect with less than 20 per cent of a basin deforested but a large increase with 50 to 100 per cent of a basin deforested. These changes occur at the local scale, but rivers of all sizes are affected when deforestation is extensive.

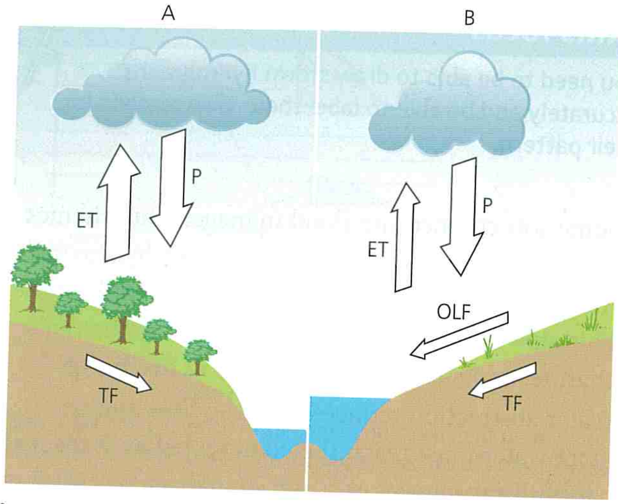

Figure 1.31a The effects of deforestation on the water cycle – localised deforestation

Before deforestation (A) much of the high precipitation (P) is returned to the atmosphere by evapotranspiration (ET). Overland flow is minimal. Most of the water that reaches the forest floor infiltrates into the soil and travels slowly to the river by throughflow, maintaining a steady flow in the river.

After deforestation (B), although the precipitation stays the same, the evapotranspiration is lower because the replacement vegetation has smaller leaves and roots and is less dense. Overland flow and throughflow occur because of the lack of vegetation. This leads to increased discharge and flashiness. This can cause localised flooding

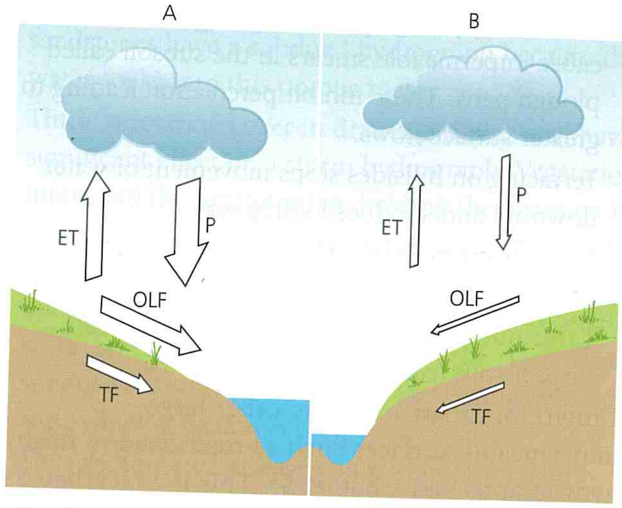

Figure 1.31b The effects of deforestation on the water cycle – extensive deforestation

Where deforestation is extensive, positive feedback can occur in the basin hydrological system. In A, because evapotranspiration is low, much of the water leaves the area in the river channel rather than being recycled continuously between the forest and the atmosphere. Once the water has left the area there is less water vapour available in the atmosphere for precipitation and so precipitation levels fall. Less water gets to the river channel and the flow is reduced

This suggests several important points about the climate, land surface and water cycle:

- If deforestation does not cause decreased rainfall via atmospheric feedbacks, discharge will likely be significantly increased throughout the entire southern Amazon (Figure 1.31a).
- If rainfall does decrease via atmospheric feedbacks the resulting decrease in river discharge may be greater than the changes without feedbacks (Figure 1.31b).
- Changes in water resources caused by atmospheric feedbacks will not be limited to those catchment areas where deforestation has occurred but will be spread unevenly throughout the whole Amazon basin by atmospheric circulation.

Soil drainage

Subsurface drainage removes excess water from the soil profile. It is carried out usually through a network of perforated tubes installed 60–120 cm below the soil surface. These tubes are commonly called 'tiles' because they were originally made from short lengths of clay pipes known as tiles. Water would seep into the small spaces between the tiles and drain away. The most common type of 'tile' now is corrugated plastic tubing with small perforations to allow water entry. When the water table in the soil is higher than the tile, water flows into the tubing, either through holes in the plastic tube or through the small cracks between adjacent tiles. This lowers the water table to the depth of the tile over the course of several days. Drain tiles allow excess water to leave the field, but once the water table has been lowered to the elevation of the tiles, no more water flows through the tiles. In most years in the UK, drain tiles have not flowed between June and October.

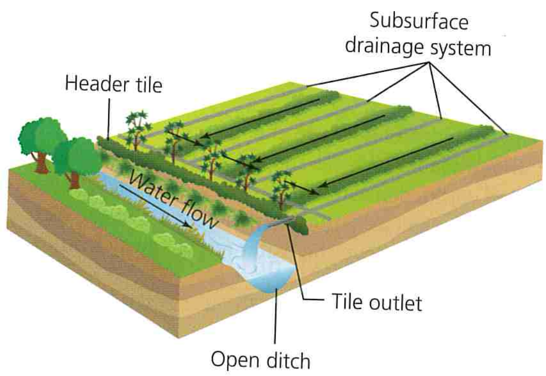

Figure 1.32 A typical tile drainage set-up

Although costly, agricultural drainage is very good for moderately to poorly drained soils. It increases the productivity of the field and helps to improve the efficiency of growers. A study by Ohio State University demonstrated that for every dollar spent on drainage the grower got back between $1.20 and $1.90 when growing corn and soybeans.

Some of the advantages of draining marginal farmland:

- The build-up of an improved soil structure, making it more friable and easier to work. It also makes it easier to achieve greater root penetration, enabling roots to travel faster and further.
- Improved aeration, which makes conditions more favourable for microorganisms to thrive. This increases the rate at which organic matter is broken down into humus and plant nutrients are mineralised into an available form. It also provides the necessary supply of air for root cell respiration.
- The increased aeration increases the ease with which the soil can be warmed. This can make possible earlier sowing of seeds, with greater likelihood of improved germination.
- Heavy machinery can work on the land without danger of compaction (and so leading to increased overland flow).
- Larger numbers of animals can be allowed to graze the land, once again without compacting the soil.

Some of the disadvantages:

- The insertion of drains artificially increases the speed of throughflow in the soil. Much more water reaches watercourses more quickly than before drainage. This can increase the likelihood of flooding and increase the range of flows in rivers. It is interesting to note that before the drainage of many floodplains in the UK from the eighteenth century onwards, rivers were more navigable than today; the annual flow regime was much more even.
- The dry topsoil can be subject to wind erosion if not properly protected. Soil loss by wind erosion has mainly been documented for sandy and peaty soils in the eastern and middle counties of England, especially arable fields in the East Midlands and East Anglia. Generally the area of England and Wales subject to wind erosion is small, although those fields that are affected are more severely eroded than by water erosion. The proportion of a field subject to wind erosion is likely to be greater than that subject to water erosion. Available estimates suggest that the mean wind erosion rate is of the order of 0.1 to 2 tonnes/ha/year, although maximum values for fields can be one or two orders of magnitude higher.
- Another major concern with regard to land drainage is nitrate loss. It can lead to eutrophication. Water draining from fields finds its way into local watercourses. There it enriches ponds, etc., with nitrogen or phosphorus. It causes algae and higher

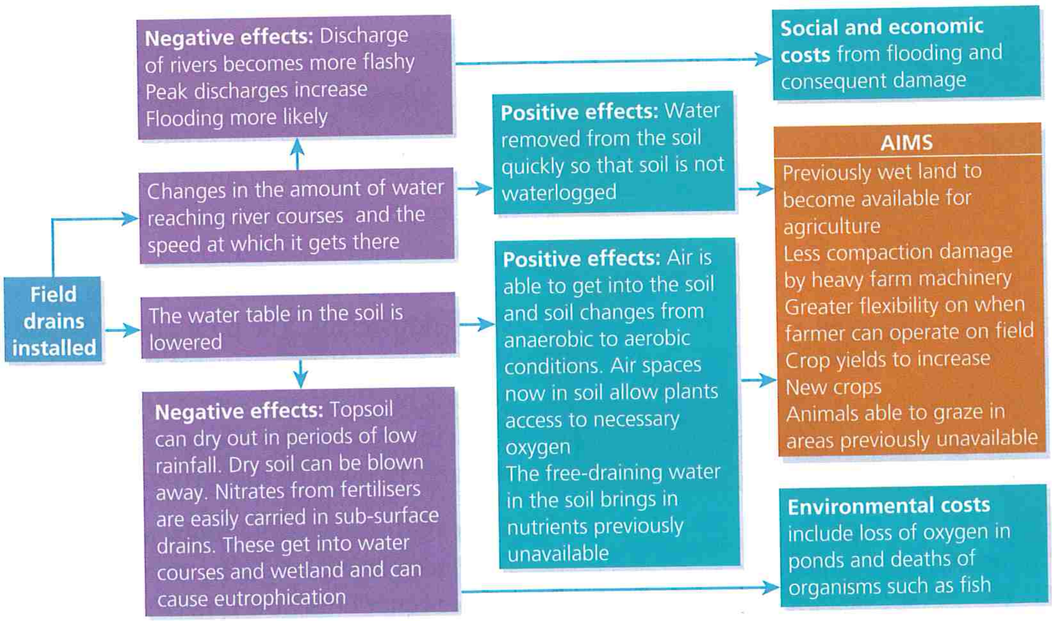

Figure 1.33 System diagram showing the effects of soil drainage

forms of plant life to grow too fast. This disturbs the balance of organisms present in the water and the quality of the water concerned.

One way to overcome some of these problems is to use controlled drainage. This keeps the water table high during the off-season when crops are not growing. The high water table increases the rate of denitrification (a process that converts nitrate to harmless nitrogen gas (N_2) as soon as the saturated soil warms up in the spring) and reduces nitrate loss to the environment.

Water abstraction

Problems can occur when the demand for water exceeds the amount available during a certain period. They happen frequently in areas with low rainfall and high population density, and/or in areas with intensive agricultural or industrial activity.

In many areas of Europe, groundwater is the dominant source of fresh water. In a number of places water is being pumped from beneath the ground faster than it is being replenished through rainfall. The result is sinking water tables, empty wells, higher pumping costs and, in coastal areas, the intrusion of saltwater from the sea which degrades the groundwater. This saline intrusion is widespread along the Mediterranean coastlines of Italy, Spain and Turkey, where the demands of tourist resorts are the major cause of over-abstraction. In Malta, most groundwater can no longer be used for domestic consumption or irrigation because of saline intrusion, and the country has resorted to expensive desalination plants.

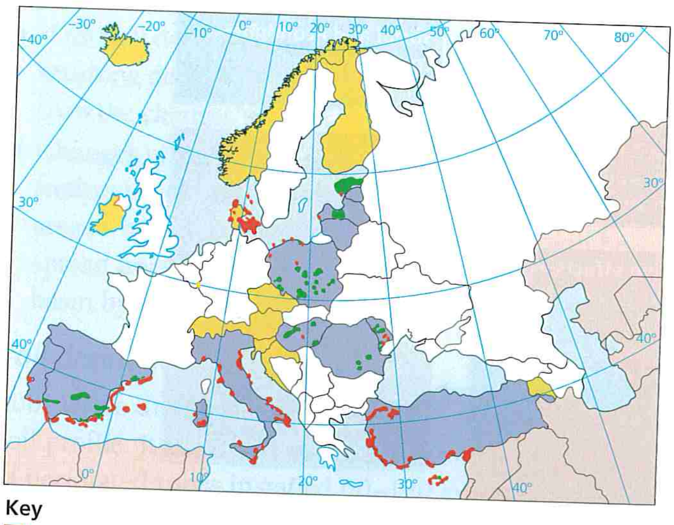

Figure 1.34 Salt water intrusion in Europe

Source: European Environment Agency

Sinking water tables can also make rivers less reliable, since many river flows are maintained in the dry season by springs that dry up when water tables fall. Groundwater also helps sustain surface reservoirs of water such as lakes and wetlands that are often highly productive ecosystems and resources for tourism as well as leisure activities. These, too, are threatened by over-abstraction of groundwater.

Irrigation is the main cause of groundwater over-exploitation in agricultural areas. Examples include the Greek Argolid plain of eastern Peloponnesus where it is common to find boreholes 400 m deep contaminated by seawater intrusion. In Italy, over-exploitation of the Po River in the region of the Milan aquifer has led to a 25–40 m decrease in groundwater levels over the last 80 years. In Spain, more than half of the abstracted groundwater volume is obtained from areas facing over-exploitation problems.

Water abstraction from the chalk of southern England

The water within the chalk aquifer of southern England is replenished by rainfall that lands on the exposed chalk hills of the North and South Downs and the Chilterns. Normally recharge takes place during the winter months when potential evapotranspiration is low and soil moisture deficits are negligible. Groundwater amounts vary seasonally, with levels rising from autumn through winter into spring. During the summer months, potential evapotranspiration generally exceeds rainfall, soil moisture deficits build up, and little, if any, percolation takes place.

In the summer water still leaves the chalk from springs as well as by abstraction from boreholes. This pattern is not constant, since rainfall varies both over time and location. Rivers fed by groundwater from chalk aquifers can have intermittent sections. These streams, often referred to as 'bournes', are a natural characteristic of chalk downlands. The positions of the springs feeding these rivers differ throughout the year, being at a greater altitude in winter and spring. If there are one or more dry winters when the effective rainfall available for recharge is low then these rivers can dry up altogether.

Some of the most acute problems with over-abstraction have been found in chalk stream systems, where up to 95 per cent of the flow is derived from underground aquifers. The catchments of chalk streams provide underground reservoirs of generally high quality groundwater which can be abstracted for public supply. Abstraction for public water supply and industry has dramatically reduced the flow in many chalk streams and, in some cases, completely dried up sections of these important rivers, particularly during dry summers when public demand is at its highest. This also has an economic impact on local communities, resulting from the inability to fish, enjoy river views due to encroaching vegetation or undergo other recreational activities.

Water abstraction in the London Basin

Figure 1.35 shows the subsurface geology of the London Basin. The chalk layers form a syncline beneath the London area with the uplands of the Chilterns to the NW and the North Downs to the SE. Precipitation on these exposed chalk hills soaks into the porous chalk where it is stored and released naturally at springs where it is in contact with either Greensand or Palaeogene rocks.

Throughout history, in London, water has been abstracted from wells and boreholes that penetrate down to the chalk. During the nineteenth century and first part of the twentieth century, the chalk-basal sands aquifer had been increasingly exploited, as a result of increased industrialisation and the associated development of groundwater sources. At the peak of abstraction in the 1960s, groundwater levels beneath central London had dropped to 88 m below sea level, creating a large depression in the water table. A smaller cone of depression also developed to the east beneath the River Roding in Essex.

Since the mid-1960s, industries, such as brewing, in central London relocated or were closed down. Economic activity turned more to service industries and commerce than heavy industry. The subsequent reduction in abstraction resulted in groundwater levels recovering by as much as 3 m/year in places by the early 1990s, leading to a gradual rebound of the water table. This then has posed the threat of rising groundwater to structures in the London Basin such as London Underground and building foundations. This led to the implementation of the General Aquifer Research, Development and Investigation Team (GARDIT) strategy to control water levels. As a result of careful management of both abstraction and artificial recharge the rise in groundwater that the GARDIT strategy was designed to arrest had largely been achieved by 2000, so this year provides a useful baseline year for comparisons.

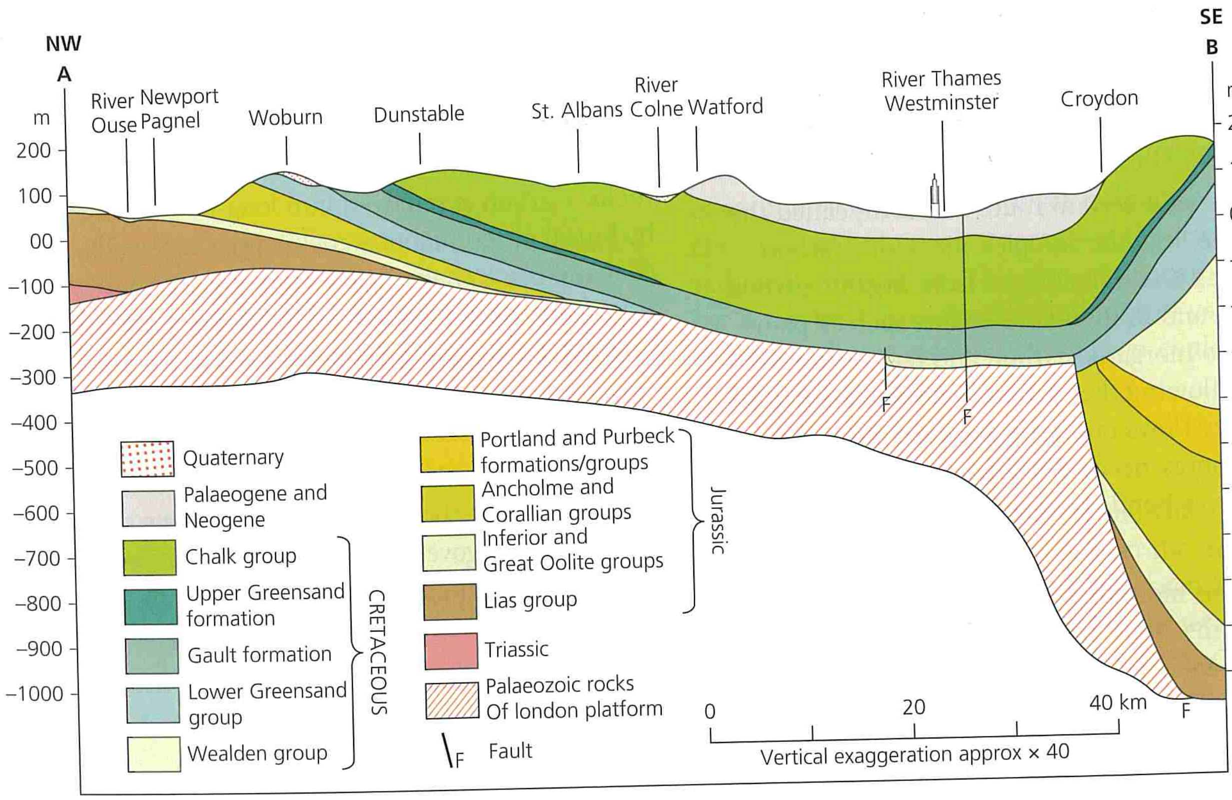

Figure 1.35 Cross section showing the confined chalk aquifer of the London Basin (BGS, 1996)

The differences in groundwater levels for January 2000 and January 2014:

- Groundwater levels in west London have risen due to limited abstraction in this area, in the order of four to eight metres since 2000 which has levelled off in recent years.
- In central and east London groundwater levels have fallen in the order of 5–7 m since 2000 as a result of increased abstraction.
- Groundwater levels have fallen more than 2 m across much of south London, with falls of up to 12 m concentrated around the many large public water supply abstractions.
- In east London, where there are chalk outcrops around the River Thames from Greenwich to Woolwich, there is a risk of saline intrusion. When groundwater levels near the river are lower than the water level in the River Thames, saline river water can enter the chalk aquifer.

1.3 The carbon cycle

Carbon (C) (from the Latin *carbo* meaning coal) is one of the most chemically versatile of all the elements. Carbon forms more compounds than any other element and scientists predict that there are more than ten million different carbon compounds in existence today on Earth. Carbon is found in all life forms in addition to sedimentary rocks, diamonds, graphite, coal and petroleum (oil and natural gas).

Carbon follows a certain route on Earth, called the carbon cycle. It is the complex processes carbon undergoes as it is transformed from organic carbon (the form found in living organisms such as plants and trees) to inorganic carbon and back again. Through following the carbon cycle we can also study energy flows on Earth, because most of the chemical energy needed for life is stored in organic compounds as bonds between carbon atoms and other atoms.

Carbon atoms move through the carbon cycle in many different forms. Some important examples of carbon compounds include:

- carbon dioxide (CO_2), a gas found in the atmosphere, soils and oceans
- methane (CH_4), a gas found in the atmosphere, soils and oceans and sedimentary rocks
- calcium carbonate ($CaCO_3$), a solid compound found in calcareous rocks, oceans and in the skeletons and shells of ocean creatures
- hydrocarbons – solids, liquids or gases usually found in sedimentary rocks
- bio-molecules – complex carbon compounds produced in living things. Proteins, carbohydrates, fats and oils, and DNA are examples of bio-molecules.

Of all these forms of carbon, we study CO_2 in most detail because it is thought that this has a profound effect on climate. It is also difficult to separate a *natural* carbon cycle from one that is affected by human activity. Human activity and associated emissions of carbon dioxide (anthropogenic CO_2) fundamentally affect the carbon cycle and so affect climate.

Origins of carbon on Earth

The primary source of carbon/CO_2 is the Earth's interior. It was stored in the mantle when the Earth formed. It escapes from the mantle at constructive and destructive plate boundaries as well as hot-spot volcanoes. Much of the CO_2 released at destructive margins is derived from the metamorphism of carbonate rocks subducting with the ocean crust. Some of the carbon remains as CO_2 in the atmosphere, some is dissolved in the oceans, some carbon is held as biomass in living or dead and decaying organisms, and some is bound in carbonate rocks. Carbon is removed into long-term storage by burial of sedimentary rock layers, especially coal and black shales (these store organic carbon from undecayed biomass) and carbonate rocks like limestone (calcium carbonate).

The major stores of carbon

A gigatonne of carbon dioxide equivalent (GtC) is the unit used by the United Nations climate change panel, the Intergovernmental Panel on Climate Change (IPCC), to measure the amount of carbon in various stores. 1 Gt amounts to 10^9 tonnes (1 billion tonnes).

Transfer (flux) of carbon within the cycle is measured in gigatonnes of carbon per year (GtC/years).