CHAPTER 2

ENVIRONMENTAL ASPECTS

2.1 General

External environmental conditions have a profound effect on the type and extent of staining on a building facade. This is especially true for deterioration processes which are initiated by rain runoff. Without rain runoff, the staining agents (dirt) would probably affect the face of the building evenly [1]. However, the rate, volume and flow pattern of rain runoff flowing on a facade is determined largely by the synergistic workings of rain, wind and sunlight. In averting staining problems, it may be useful to understand the manner by which pollutants in the atmosphere are transported to the buildings and adhered to the facade surfaces, and the ways in which dirt is subsequently redistributed by rain runoff over the facade. Therefore, before the design team embarks on the design, materials and system selection for the facade, they should consider carefully the atmospheric conditions the building is going to be exposed to including:

- Rain
- Wind
- Sunlight
- Pollutants

With a good understanding of the environment (its microclimate and its pollution) in which the building is to be built, a risk analysis can be made right from the planning stage, and this enables the design team to identify areas that require special attention [2]. Materials that are suitable for these situations can then be selected and design features that are able to control runoff flow be incorporated.

2.2 Rain

Rainwater plays a central role in many of the destructive mechanisms that a building experiences, such as dimensional change, corrosion, leaching, efflorescence, and water penetration, which may lead to the deterioration of internal finishes [3]. In the staining of facades, rainwater is the initiator of the process. Movement of water over the facade of the building will result in either washing or deposition of dirt, causing the disfigurement of the building's appearance if such effects are concentrated at different locations. Water is also a major factor in leaching and efflorescence processes, as well as in promoting biological growth, all of which will result in the staining of the building facade.

From a study carried out on the rainfall data for a period of 10 years (1988–1997), it was observed that Singapore received an average of 238.5cm of rainfall [4]. Figure 2.1 shows the 5 major regions of Singapore (North, South, East, West and Central) and Figure 2.2 shows the average rainfall in these respective regions. It appears that there is little difference in the average rainfall level between each region for the period 1988–1997, with the lowest rainfall recorded in the East.

Hence, in Singapore the general location of a building does not affect the amount of rainfall and the extent of the washing effect that it will receive.

2.3 Wind

Most rainfalls are accompanied by wind, which makes it important to consider a building's exposure to the prevailing wind direction. One fundamental effect of wind during rainfall is that it will change the direction of fall of raindrops so that they impinge on vertical surfaces instead of falling parallel to the surfaces [5,6,7]. Wind force does not only bring about driving rain but may also alter the pattern of runoff flow

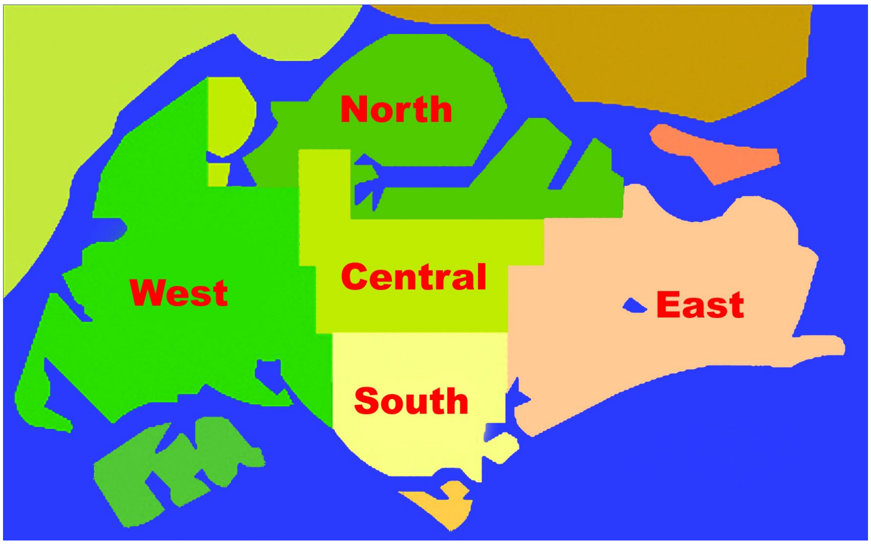


Figure 2.1. Map of Singapore divided into 5 major parts [4].
(Source: http://intranet.mssinet.gov.sg/nowcast/)

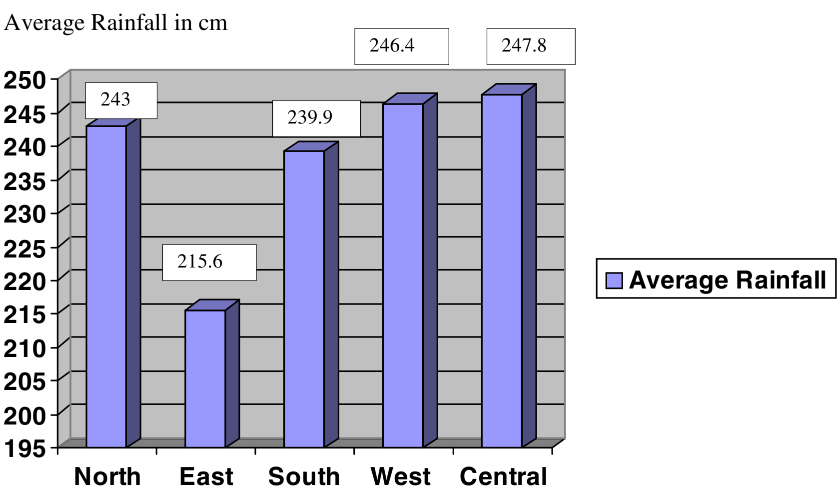
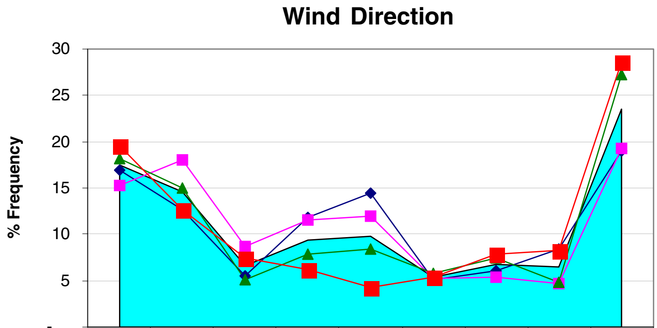


Figure 2.2. Average rainfall in the 5 parts of Singapore [4].

on the facade. Since the direction from which the wind blows changes throughout the year, the direction from which rain will impinge on the building facade will vary accordingly.

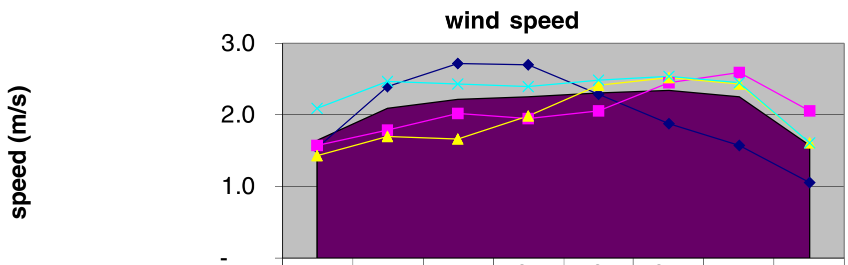
From a study conducted to determine the predominant direction and the speed of wind in Singapore, it was found that over a period of 10 years (1988–1997), the general prevailing wind direction for all sectors is in a N to NE sector direction, followed by the S to SE sector direction (Fig. 2.3). The range for the 10-year average wind speed is small, ranging between 1.6 to 2.3 m/s. Wind from the N and NW sectors have generally lower wind speed (Fig. 2.4).

The quantity of rainwater, the velocity and the angle at which rain hits the building varies significantly at different parts of a building. Wind driven rain is defined as “rain carried along by wind at an angle to the vertical” [5,6,7]. In Singapore, rainfalls are usually accompanied by wind with speeds of between 1.6 to 2.3 m/s. Generally, winds from N and NW sectors have lower wind speeds (Fig. 2.4). This wind speed increases significantly with respect to the height of the building. Wind speeds of up to 20 m/s have been recorded on the 20th storey of buildings in various parts of Singapore [6].



	N	NE	E	SE	S	SW	W	NW	Calm
Average	17.5	14.6	6.7	9.4	9.8	5.4	6.7	6.5	23.6
Singapore Changi Airport	16.9	12.7	5.5	11.9	14.5	5.1	6.0	8.4	19.0
Paya Lebar Air Base	15.3	18.0	8.7	11.5	12.0	5.2	5.3	4.7	19.3
Tengah Air Base	18.2	15.0	5.1	7.9	8.4	5.8	7.5	4.8	27.3
Seletar Aerodome	19.5	12.6	7.4	6.2	4.2	5.4	7.9	8.2	28.6

Figure 2.3. 10-year averaged percentage frequency of mean wind direction [4].



	N	NE	E	SE	S	SW	W	NW
Average	1.7	2.1	2.2	2.3	2.3	2.3	2.3	1.6
Singapore Changi Airport	1.5	2.4	2.7	2.7	2.3	1.9	1.6	1.1
Paya Lebar Air Base	1.6	1.8	2.0	2.0	2.1	2.5	2.6	2.1
Tengah Air Base	1.4	1.7	1.7	2.0	2.4	2.5	2.4	1.6
Seletar Aerodome	2.1	2.5	2.4	2.4	2.5	2.5	2.5	1.6

Figure 2.4. 10-year averaged surface wind speed [4].

The dominant wind direction affects how rain will strike the facade and how the resultant rain runoff will flow and redistribute the dirt on the facade. Beijer (1980) [7] reported that:

- Less than half the quantity of rain that should pass through an equivalent cross-sectional area of "free air" is caught by the external wall. This applies regardless of the wind force.
- The top parts of the external wall receive much more rain than the lower parts.
- Raindrops move almost parallel to the lower sections of the external wall.

From such analysis it is expected that in Singapore, wind-driven rain is predominant from N and NE directions. Facades orientated towards these directions may receive more rain impacting on them, resulting in greater washing and deposition of dirt. Furthermore, the angle made between the raindrop and the vertical surface will be greater for facades facing SE, S, SW and W due to the greater speed of wind at these orientations. This may give rise to differing staining patterns due to sheltering effect especially on facades that have projections.

When wind moves across a building, it changes its direction especially around the edges of a building. Raindrops that are driven by the wind would not be able to follow this directional change and would strike the facade. Hence, the wetting pattern for a tall building would be heavier at windward corners, projections and parapets. The washing effect at such areas would thus be relatively stronger [7].

Once the raindrops impinge on the facade and generate enough runoff to run over the face of the wall, its flow would be rather vertical but this is also subjected to the force of lateral winds that has the ability to alter the pattern of flow [3]. This wind force increases as the building height increases.

2.4 Sunlight

Sunlight plays an important role in affecting the formation of stains on a facade. Some surfaces may be exposed directly to long periods of sunshine while others may be sheltered and remain in constantly damp conditions. The intensity and duration of sunlight that a surface receives affect the limit of runoff flow, the type of biological stains and hence the pattern of staining. A facade's exposure to sunlight may be affected by its orientation since the north and south facing facade generally receive less sunlight compared to the east and west facing ones [8,9,10,11]. The presence of adjacent buildings and other structures may also provide a sheltering effect. These may result in the facade having a slower drying process after it has been wetted, leaving it damp for longer periods and therefore promoting biological staining. The orientation and location of facades thus may have implications on the extent of its staining.

Adopting the horizontal coordinate system, the direction that the sunlight strikes the earth can be represented by the solar altitude angle and the solar azimuth angle. The solar altitude angle describes how high the sun appears in the sky (Fig. 2.5), and is measured between an imaginary line drawn between the observer and the sun and the horizontal plane the observer is standing on. This angle is negative when the sun drops below the horizon. The solar azimuth angle is the angular distance between due South and the projection of the line of sight to the sun on the ground (Fig. 2.6). A positive solar azimuth angle indicates a

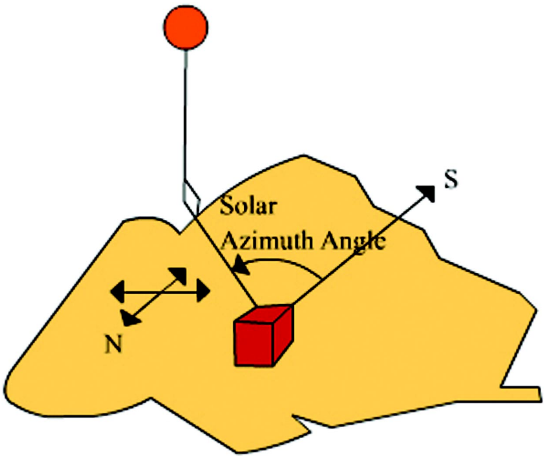


Figure 2.5. Solar altitude angle.

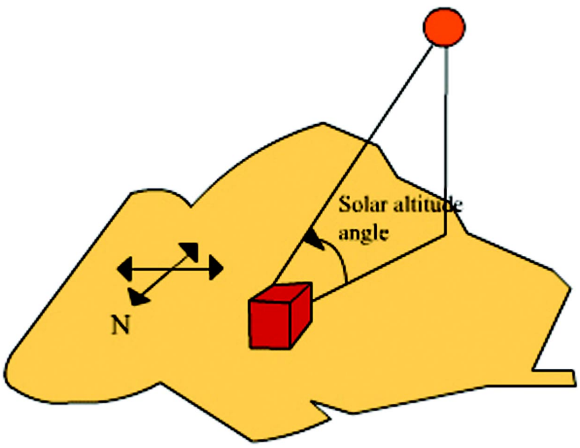


Figure 2.6. Solar azimuth angle.

position East of South, and a negative azimuth angle indicates a position West of South. The angles vary at different times of the day and at different locations due to the earth's orbit around the sun and its own orbit on its axis [8].

Solar altitude angles and azimuth angles have been measured extensively in various independent studies carried out to determine sky luminance in Singapore [8,9,10,11]. In one such study on sky luminance of Singapore in 2000, it was found that solar altitude angle increased from 0700 hrs and peaked at about 1300 hrs in the afternoon with a value of 75 degrees (average) before decreasing as it approached 1900 hrs [11]. The solar azimuth angle on the other hand was found to be about 90 degrees (average) at 0700 hr indicating that the sunlight was shining from the east and was about –90 degree (average) at 1900 hrs indicating that the sunlight was shining from the west. Generally, for the months of April to September 2000, facades facing North received sunlight mainly from ENE and WNW directions and from the North directly for a short period in the afternoon while facades facing the South did not receive any sunlight. For the months of October to March 2000, facades facing South received sunlight mainly from ESE and WSW directions and from the South directly for a short period in the afternoon while facades facing the North did not receive any sunlight. The findings were supported by results from actual measurements [9, 10]. North and South facing surfaces remain wetter for longer periods after wetting as compared to the East and West facing facades.

In addition, for every part of a facade to receive sunlight daily (assuming a yearly minimum solar altitude angle of 65 degrees [11], the adjacent building's height must also not be more than 2.14 m high for every 1 m the adjacent building is away from the facade (Fig. 2.7).

2.5 Pollution

Singapore uses the guidelines of World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA) in assessing its pollution levels. Since 1990, the concentration of pollutants in the air were generally at very low levels and the Pollutant Standard Index (PSI) fluctuated between good and moderate levels [12]. The complex process of staining begins with the deposition of staining agents on the facade. There are two types of staining agents that can affect

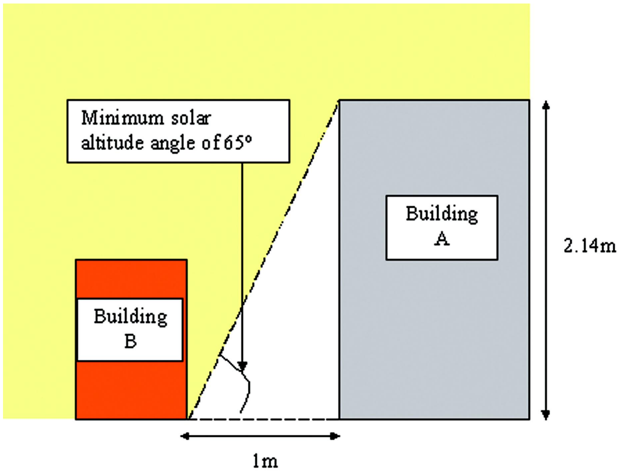


Figure 2.7. Permitted height of adjacent building if a facade is to receive sunlight daily.

building facades: non-biological and biological staining agents. These staining agents may be carried by the wind and deposited directly on the facade or they can be deposited in solution by the rainwater.

2.5.1 Non Biological Staining Agents

Non-biological staining agents that build up as dirt stains on buildings are a result of air pollution from human activities. Pollution sources that emit pollutants into Singapore's atmosphere include:

- Industrial plants and presence of pollutants emitting processes
- Vehicular traffic on heavily utilised roads
- Airborne dust from neighbouring countries

Pollutants from these sources can vary in sizes from molecular to particulate. They can be grouped according to their sizes. Table 2.1 shows some common pollutants in air [13,14].

Molecular pollutants such as sulphur dioxide are present in the air and they usually dissolve in rainwater to form acidic rain that corrodes and attacks facade materials causing localised losses of material.

Table 2.1. Common pollutants in air [13, 14].

Pollutants	Examples	Sizes	Sources	Possible Effects
Aerosols	Sulphur dioxide (SO_2).	Gaseous	Burning of fuels.	Formation of acid rain. Reaction with water and other materials to form sulphates and chlorides, causing destruction to facade materials.
Soot or black smoke	Smoke from tobacco, coal, fuel oil, metallurgical industry.	$< 1\mu m$	Imperfect combustion.	Transported by air and deposited on facades, causing stains.
Coarse particulate matter	Ash, dust, rock debris, mineral dust.	$> 1\mu m$	Unburnt fuel and dust from roads and industries.	Transported by air for short distances and deposited on horizontal or sloping surfaces to form stains.

Particulate matters in the air generally comprise dust, smoke and suspended particles. Dust particles being large and heavy, settle quickly and will not affect large areas. Smoke and suspended particles being smaller and lighter remain in the atmosphere for a longer time and affect larger areas. The main sources of particulate matter in Singapore are fuel-burning equipment such as boilers and furnaces, motor vehicles and construction sites. In the assessment of the effects that air pollutants may have on a building facade, it may be important for the design team to consider:

- The conditions of adjacent buildings as it would give an accurate indication of the level of pollutants and their impact on the facades.
- Proximity of proposed building to industrial plants and processes.
- Proximity to main roads and expressways.
- Up-to-date published information on pollution levels.
- Seasonal increase in pollutant concentration due to migrating pollution from neighbouring countries.

2.5.2 Biological Staining Agents

Biological staining agents might also bring about staining to the facade (Fig. 2.8). In Singapore, staining of facades due to biological staining agents can be traced to a number of diverse plant groups such as algae, fungi, mosses, ferns and figs. In land-scarce countries like Singapore where homes and offices are mostly high-rise, the disfigurement of facades of buildings by algae has attracted the most attention [15]. The main reason for this is the disfigurement of the facade and the costs involved in removing such stains.

Algae can be distinguished from fungi by their characteristic green colour due to the presence of chlorophyll. They may also be orange or blue green in colour depending on the amount of other pigments within it. On the other hand, fungi is colourless but may become blackish or coloured as they become reproductive [15,16,17]. Algae thrive best where there is sun, moisture and nutrients. Singapore's tropical climate offers an abundance of sunlight and rainfall for algae to grow. Dirt that is blown off the road and retained on the facade becomes a source of nutrients. As such, algae are found mainly outdoors on external facades. Species of algae that may be found on the facades of Singapore's buildings are *trentepohlia odorata, Chlorococcum* and an *Alga* comprising of *Scytonema*, *Schizothrix, Anacystics* (Table 2.2) [18,19].

On surfaces shaded from the direct rays of the sun and where humidity level is high, fungi rather than algae are the organisms that are likely to proliferate. Unlike algae, fungi are unable to synthesise their own organic food and thus have to rely on the medium on which they are growing to provide the nutrients necessary for their growth. Also, fungi begin to grow when the relative humidity of the surface exceeds 70%. For these reasons, they are usually found on internal surfaces of buildings such as bathrooms, kitchen, ceiling boards, wallpapers and glass panels [20].

Other than algae and fungi, biological growth on building facades may also be in the form of mosses, ferns or small plants (Table 2.2). Mosses are small plants that form mat-like patches on walls of old buildings [16]. Ferns and other small plants growing on walls are much

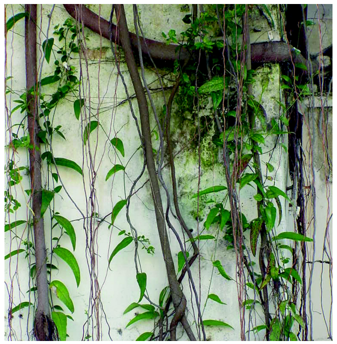
Table 2.2. Common types of biological agents found commonly on external walls of buildings in Singapore [15,16,17,18].

Biological Agent	Characteristics	Conditions for Growth
Algae    	When conditions are ideal, algae will appear in 1 to 2 years time. It may appear initially as either light green, blue green or orange coloured filaments or powder which may be slimy when wet. Over time, dirt may collect over the mycelium to result in blackish and conspicuous stains. Common species of algae in Singapore are *Trentepohlia odorata, Chlorococcum* and alga comprising of *Scytonema, Schizothrix, Anacystics*.	Direct and prolonged exposure to sunlight. Surface should be wet during rain. The degree of exposure and the amount of moisture available will dictate the type of algae that will colonise. Sloping surfaces such as ledges of window sills, balconies and verandahs are areas most prone to algae attack. Usually brick, concrete or rendered surfaces that are highly absorbent and textured will support such growth.

Contd. **Table 2.2.**

Biological Agent	Characteristics	Conditions for Growth
Moss  	Patches of small, mat-forming plants. It traps dirt and soil over time to result in a black carpet. Has good water holding ability due to its thickness.	Humid areas such as cracks that retain moisture and dirt. Usually appear after algae have proliferated. Further improves conditions that are suitable for higher plants such as ferns and small plants.
Ferns  	Higher plant species. Roots are easily visible. They retain water well and improve conditions for further biological infestation. Common fern species are *Pteris vittaata*, *Nephrolepis biserrata*.	Usually appear on walls of old buildings. Cracks in walls that have accumulations of soil and abundant moisture provide conducive environments for growth to initiate.

Contd. **Table 2.2.**

Biological Agent		Characteristics	Conditions for Growth
Other plants 		They may be typical ornamental plants usually kept in pots. They should be removed completely when growth is detected. That area of the wall should be restored by patching and painting to inhibit future growth.	May be found together with moss and ferns. Growth is hastened by deposition of seeds from nearby potted plants placed along window sills and balconies of the same building.
Strangling/ climbing figs 		Rapid growth. Roots are usually large in girth and fills up the crack that it originates from. Branch roots usually extend downwards to the ground so as to draw water and nutrients from soil. Common species of strangling figs include *Ficus religiosa, Ficus microcarpa and Ficus benjamina.* Common specie of climbing figs is *Ficus pumila*.	Growth originates from cracks in walls and from ledges. Lack of maintenance of facade will allow figs to thrive and cause serious damage to the facade. Over time, figs and extending roots may totally cover the building facade.

more visible forms of biological staining and should be removed prior to further weathering of surface.

Strangling figs are plants that propagate through dispersion by birds. They usually grow out of crevices in walls and their roots extend downwards toward the ground [15]. They should be removed as soon as possible because growth of their roots over time may cause pressure to be exerted on the cracks, resulting in widening of cracks. Climbing figs on the other hand, are usually grown on walls deliberately for aesthetics purposes. They require regular pruning in order to maintain their aesthetic qualities (Table 2.2).

Besides being aesthetically unpleasant, biological growth on facades may also cause deterioration and further weathering to the wall (Fig. 2.9) and if occurring internally, may also manifest to become an environmental health hazard. Preventive maintenance should be carried out to eradicate biological staining. This may involve the use of paint specified to SS 345: 1990 or similar finishes that are designed to prevent or combat biological growth [21,22]. In addition, wall design should include provisions for proper channeling of runoff so that runoff is not concentrated at particular areas.

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