

University of Pretoria etd – Bothma, J (2004)

**Landscape and architectural devices for
energy-efficient South African suburban
residential design**

by

Johan Bothma

Submitted in partial fulfillment of the requirements for the degree

Master of Landscape Architecture

in the

Department of Architecture

Faculty of Engineering, Built Environment and Information Technology

University of Pretoria

Study leader: Prof. Gwen Breedlove

August 2004

Abstract

The study relates international knowledge of climatically responsive and energy-efficient design to work done in South Africa. It also explores the relevance of design devices from international regions to the climates of this country. The research approach explores existing analyses of the main climate regions and the effects of climate factors on human comfort in each, in order to derive appropriate design solutions for the climate of South Africa.

In South Africa obstacles exist in the face of energy efficiency. The cheapness of electricity to the consumer and the virtual non-existence of appropriate legislation appear to be two of the most significant obstacles. Design and subsequent construction of suburban residences is carried out with little regard for climatic context. Water is shown to be a particularly scarce and unevenly distributed commodity, which the affluent have greater access to and consume in greater quantities. However, it is demonstrated that the South African climate is virtually ideal for several climate-responsive energy-efficiency techniques. Especially due to the high solar radiation levels there is potential for various active and passive solar design techniques and technologies.

The impact of atmospheric temperature and humidity, wind, radiation and precipitation on human comfort is investigated. Humidity and wind are demonstrated to be very influential on human comfort, whereas radiation and wind are the most easily manipulated through design. Furthermore, the specific topography and location of a site can influence the microclimate and solar access of an area to a significant degree.

The South African climate is predominantly either hot semi-arid or temperate. Most of the western interior is hot arid whereas the eastern interior and highveld is predominantly temperate, with temperatures increasing to the north and decreasing to the south. The only cool region of the country is found in the highlands of the Drakensberg, with a significant portion of the eastern coast being hot humid.

Methodologies and guidelines for both layout, or macro design, and detailed design of residential suburbs are explored. The manipulation of solar radiation, sunlight and wind, as well as the management of rainwater and used household water is explored. It is shown that

designing suburbs to create access to solar radiation forms the basis of solar design, with solar access control, material and surface treatment largely determining the success of individual designs. Wind manipulation is achieved mainly through planting design, influencing mostly heat loss and gain ratios into buildings. Effective household water management can substantially reduce its consumption. Further research is needed in all aspects of climate-responsive design, especially classification of the South African climate and development of design techniques adapted to this context.

Keywords

Climate, residential, design, energy efficiency, material, construction, site, layout, orientation, topography, hot arid, hot humid, temperate, cool, building, landscape, architecture, solar radiation, ventilation, irrigation

Opsomming

Hierdie studie bring internasionale kennis oor klimaat-sensitiewe en energiedoeltreffende ontwerp in konteks met soortgelyke werk deur Suid-Afrikaners. Die studie ondersoek ook bestaande ontledings van die hoof-klimaatstreke en die uitwerking van klimaatfaktore op menslike gemak. Sodoende beoog die studie om gepaste ontwerp oplossings vir die klimaat van die land voor te stel.

Verskeie struikelblokke bestaan in die pad van energiedoeltreffendheid in Suid-Afrika. Die lae prys van elektrisiteit en afwesigheid van minimum regulasies blyk twee van die belangrikstes te wees. Ontwerp en konstruksie van voorstedelike wonings geskied sonder inagneming van klimatologiese konteks. Water blyk ook 'n besonders skaars hulpbron te wees. Daar is groter toegang daartoe in meer gegoede en word daar in groter hoeveelhede gebruik. Dit word egter getoon dat Suid-Afrika se klimaat hoogs geskik is vir klimaat-sensitiewe ontwerp, veral vanweë die hoë vlakke van son energie, aanwendbaar volgens beide aktiewe en passiewe benaderings.

Die belangrikheid van atmosferiese temperatuur en humiditeit, wind, son energie en neerslag op menslike gemak word ondersoek. Humiditeit en wind blyk die grootste invloed op menslike gemak uit te oefen, terwyl son energie en wind die optimaal deur ontwerp gemanipuleer kan word. Verder speel die spesifieke topografie en ligging 'n belangrike rol in die mikroklimaat van 'n terrein.

Die Suid-Afrikaanse klimaat is oorwegend of warm en semi-arië, of gematig. Meeste van die westelike binneland is warm-arië, terwyl die westelike binneland en hoëveld gematig is, met 'n gemiddelde toename in temperatuur na die noorde. Die enigste koel streek is te vinde in die Drakensbergse hoogland, en 'n beduidende deel van die Ooskus is warm en vogtig.

Metodologieë en riglyne vir uitleg, grootskaalse ontwerp en detailontwerp van residensiële woonbuurte word ondersoek. Die manipulasie van uitstraling, sonlig en wind, sowel as die bestuur van reënwater en huishoudelike afloop word aangespreek. Daar word gewys dat toegang tot sonlig die basis vorm vir woonbuurte wat vir son energie benutting beplan word, terwyl beheer van sonlig, keuse van materiaal en oppervlakbehandeling die sukses van

individuele ontwerpe bepaal. Windbeheer word hoofsaaklik toegepas deur plantontwerp en strukturele elemente, deur die verlies van hitte en opname deur geboue te beheer. Effektiewe residensiële waterbeheer kan die gebruik daarvan dramaties verminder. Daar word ook getoon dat meer ondersoek na veral die klassifikasie van die Suid-Afrikaanse klimaat, ten opsigte van klimaat-sensitiewe ontwerp, en die ontwikkeling van ontwerpriglyne in daardie konteks nodig is.

Sleutelwoorde

Klimaat, residensieel, ontwerp, energie doeltreffend, materiaal, konstruksie, terrein, uitleg, oriëntasie, topografie, warm en aried, warm en humied, gematig, koel, gebou, landskap, argitektuur, uitstraling, ventilasie, besproeiing.

TABLE OF CONTENTS

Abstract	ii
Keywords	iii
Opsomming	iv
Sleutelwoorde	v
TABLE OF CONTENTS	vi
List of figures	x
List of tables	xiii
List of abbreviations	xiv
Glossary of terms	xv
1 CHAPTER I – INTRODUCTION.....	1
1.1 Background for the study: the problem in context	1
1.1.1 Introduction	1
1.1.2 Energy and resource consumption crisis in South Africa and the world	1
1.1.3 Energy efficiency as an afterthought in South African urban planning and design	5
1.1.4 Cognitive dissonance in urban design.....	6
1.1.5 Summary	8
1.2 Motivation.....	8
1.2.1 Introduction	8
1.2.2 Potential contributions of residential suburbs towards energy efficiency.....	9
1.2.3 Potential for energy-efficient and climatically responsive suburbs in South Africa.....	10
1.2.4 The role of landscape design in the energy efficiency of South African higher income suburban residential areas	12
1.2.5 The role of structuralised urban design codes within a socio-political and economic setting.....	13
1.2.6 Summary	15
1.3 Problem statement, hypotheses and research methodology	16
1.3.1 The problem statement.....	16
1.3.2 Hypothesis one: The climate factors that influence human comfort can be identified and described	16
1.3.3 Hypothesis two: The climatic character of the landscape can be identified and described	17
1.3.4 Hypothesis three: Climate design devices for the climate regions, that enable energy efficiency, can be identified and described...	18
1.4 Delimitations and boundaries of the study.....	18

1.5	Present state of information.....	20
1.5.1	Preliminary literature overview, locally and abroad.....	20
1.5.2	Computer programs and database resources available to urban designers.....	23
2	CHAPTER II – ESTABLISHING THE CLIMATIC FACTORS THAT INFLUENCE HUMAN COMFORT	25
2.1	Climatic factors that dictate energy efficient climatic landscape design.....	25
2.1.1	Introduction	25
2.1.2	Temperature.....	25
2.1.3	Humidity	27
2.1.4	Wind.....	29
2.1.5	Radiation	31
2.1.6	Precipitation.....	32
2.1.7	Summary	33
2.2	Influence of latitude and physical site character on solar access.....	33
2.2.1	Introduction	33
2.2.2	Site latitude, sun and azimuth angles	34
2.2.3	Aspect and site physical location.....	37
2.2.4	Site slope.....	39
2.2.5	Summary	40
3	CHAPTER III – THE CLIMATIC DESIGN REGIONS	42
3.1	The South African context	42
3.1.1	Introduction	42
3.1.2	Geo-climatic classification of the country by Schulze (1965).....	42
3.1.3	Phyto-geographical climatic analysis according to Kruger (2003) 43	
3.1.4	Climatic classification of the country by Napier (2000).....	44
3.2	Describing the four main climate regions	45
3.2.1	Introduction	45
3.2.2	Hot humid climate	46
3.2.3	Hot arid climate.....	46
3.2.4	Temperate climate.....	49
3.2.5	Cool climate	50
3.2.6	Summary	52
5	CHAPTER V – LANDSCAPE DESIGN DEVICES FOR ENERGY EFFICIENCY IN THE CONTEXT OF THE SUBURBAN RESIDENCE	54
5.1	Introduction	54
5.2	Suburban structure and layout	55
5.2.1	Initial considerations	55
5.2.2	Street and lot orientations.....	56
5.2.3	Streetscapes and planting	60

5.2.4	Topographical and development density considerations.....	63
5.2.5	Suburban layout in different climatic contexts.....	67
5.3	Passive solar design.....	71
5.3.1	Passive versus active solar design.....	71
5.3.2	Passive solar design and temperature regulation – the flywheel effect	72
5.3.3	Passive solar design and materials.....	74
5.3.4	Passive solar design and building shape and orientation.....	78
5.4	Wind breaks.....	82
5.4.1	Vegetative and built windbreaks.....	82
5.4.2	Shelterbelt structure.....	84
5.4.3	Shelterbelt density and visual porosity.....	88
5.4.4	Shelterbelts and oblique winds.....	89
5.4.5	Other effects of shelterbelts on microclimate.....	91
5.4.6	Built windbreaks.....	92
5.4.7	Windbreaks and wind management in different climatic contexts	94
5.5	Solar access control.....	96
5.5.1	Building shape and orientation.....	96
5.5.2	Sun and shade control and daylighting.....	99
5.5.3	Surface treatments and colour.....	106
5.5.4	Solar water heating.....	112
5.6	Water and runoff management.....	114
5.6.1	The need for water conservation.....	114
5.6.2	Xeriscaping.....	115
5.6.3	Evaporation prevention.....	118
5.6.4	Runoff utilisation.....	120
5.6.5	Water re-use.....	124
5.6.6	Evaporative cooling.....	127
6	CHAPTER VI - CONCLUSIONS, SHORTCOMINGS AND FURTHER RESEARCH.....	129
6.1	Conclusions.....	129
6.1.1	Introduction.....	129
6.1.2	The problem of residential energy inefficiency in South Africa and the potential for change.....	129
6.1.3	Climatic factors and the influences of site.....	130
6.1.4	The climate of South Africa.....	131
6.1.5	Considerations regarding energy efficiency in South Africa ...	131
6.1.6	Climate-responsive design in the suburban context.....	132
6.1.7	Current shortcomings in the field.....	134
6.2	Recommendations for further research.....	134
6.2.1	Introduction.....	134

6.2.2	Climatic design-orientated assessments of the climate of South Africa	134
6.2.3	Climate-responsive design techniques in the South African context	135
6.2.4	Energy-efficient building codes and legal requirements	135
6.2.5	Embodied energy and financial considerations	135
6.2.6	Urban density and transport considerations	136
6.2.7	Retrofit of existing buildings for energy efficiency and climate-responsiveness.....	136
6.2.8	Design of communally integrated energy efficiency measures	136
REFERENCES.....		138
SUGGESTED READING.....		152
APPENDIX A: GEO-CLIMATIC CLASSIFICATION OF SOUTHERN AFRICA, SUMMARISED FROM SCHULZE 1965:313-322.....		154
APPENDIX B: CLIMATIC CLASSIFICATION OF SOUTH AFRICA ACCORDING TO NAPIER (2000:9.1-9.11)		162
APPENDIX C: URBAN AND BUILDING RESPONSES TO GEO-CLIMATIC ZONES OF SOUTHERN AFRICA AS CLASSIFIED BY SCHULZE (1965), SUMMARISED FROM HOLM 1996:14-78		168
APPENDIX D: CLIMATIC CLASSIFICATION OF SOUTH AFRICA ACCORDING TO KRUGER (13-11-2003)		173

List of figures

Figure 1.1 Urban sprawl in a Pretoria suburb	6
Figure 1.2 North-facing buildings of the Forbidden City in Beijing, China (ccf-dbs, accessed 18-05-2004)	14
Figure 2.1 An increase in latitude causes a decrease in the incidence angle and concentration of solar radiation	26
Figure 2.2 The human comfort zone represented on the psychrometric chart (Holm 1983:19).....	30
Figure 2.3 Specular and diffused reflections (Mazria 1979:16).....	32
Figure 2.4 The skyspace of a solar collector (Zanetto 1984:99).....	34
Figure 2.5 Annual variation of solar radiation with latitude.....	35
Figure 2.6 Concentration of solar radiation is determined by the angle of incidence and the angle of the slope	35
Figure 2.7 The apparent path of the sun through the sky for a low and high latitude position (adapted from Strahler 1969 as shown in Oliver 1973:229)	36
Figure 2.8 A method to determine the position of the sunrise and sunset position for any given latitude during the equinoxes and solstices.....	37
Figure 2.9 Aspect in relation to sun angles	38
Figure 2.10 Different shade lengths on north and south slopes.....	39
Figure 2.11 Shadows decrease on northern slopes and increase on southern slopes when site slope increases	40
Figure 2.12 The elements of site slope and aspect that influence passive solar design (based on Erley and Jaffe 1979:16, Markus & Morris 1980:172).....	41
Figure 3.1 The geo-climatic zones of South Africa according to Schulze (1965:313).....	43
Figure 3.2 Phyto-geographical climatic analysis of South Africa according to Kruger (13-09-2003).....	44
Figure 3.3 The climatic zones of South Africa according to Napier (2000:9.3.1)	45
Figure 3.4 A third of the surface of the earth is arid or semi-arid (Askin 1986, accessed 05-11-2003)	48
Figure 5.1 Site and road layout determines passive solar utilisation potential (Carter and de Villiers 1987:5-6)	56
Figure 5.2 Different street- and lot layout configurations to optimise the solar access zones of each lot, for different situations (Total Environment Centre 1982:10-13)	58
Figure 5.3 Street tree placement to ensure solar access to different lot sizes and street widths.....	59

Figure 5.4 Strategically placed street trees to shade reduced road surfaces during summer.....	61
Figure 5.5 Wind speed profiles over flat open country and urban areas or large farmsteads (Clark 1999:105).....	61
Figure 5.6 The influence of pronounced vertical and rolling topographical landforms on wind speed and airflow (Clark 1999:106).....	62
Figure 5.7 Photos illustrating the amount of vegetative cover found in two typical eastern Pretoria neighbourhoods	62
Figure 5.8 Greater development density is possible on north-facing slopes than on south-facing ones.....	64
Figure 5.9 Thermal influences operating on spaces within buildings (Matthews 1987:30)	73
Figure 5.10 Internal temperature moderation through heavyweight construction (Hyde 2000:189).....	74
Figure 5.11 Schematic diagram of roof lawn sample (Onmura <i>et al</i> 2001:654)	77
Figure 5.12 Decrease of heat flux into a building from the roof due to lawn roof garden (Onmura <i>et al</i> 2001:657)	78
Figure 5.13 Taxonomy of environmentally determined building forms (Hawkes <i>et al</i> 2002:6 after Olgyay 1963)	79
Figure 5.14 Proportions of rectangular versus courtyard form (Hinrichs 1988:57)	80
Figure 5.15 Influence of built form on heating requirements (Owens 1986:42 after BRE 1975).....	81
Figure 5.16 Entrance vestibule used to create interior temperature buffer room	82
Figure 5.17 Sun porch used to create exterior temperature buffer zone.....	82
Figure 5.18 Schematic diagram of wind flow behind a porous barrier (Nelmes, Belcher & Wood 2001:305)	84
Figure 5.19 Schematic diagram of wind behind solid windbreak relative to free stream velocity at 2 m above the ground (Brown & Gillespie 1995:129 after Geiger 1965)	84
Figure 5.20 Poor vertical layering of a shelterbelt will cause air movement underneath or through the windbreak	86
Figure 5.21 Sloped shelterbelt profiles and uniform configurations are less effective at reducing wind speed than vertical, irregularly composed ones	86
Figure 5.22 Shelterbelts with smooth upper surfaces are less effective at reducing wind speed than ones with irregular upper surfaces.....	87
Figure 5.23 Wide shelterbelts have a shorter downwind area of protection than do narrower windbreaks of a similar height and composition (Panfilov 1940 as shown in Robinette 1983b:35).....	87

Figure 5.24 Wind is accelerated through a gap in a windbreak (Caborn 1957 as shown in Heisler 1984:170)	88
Figure 5.25 The influence of different density shelterbelts on the velocity of the wind, measured at a height of 1.4 metres from the surface (van der Linde 1962, as shown in Robinette 1983b:22).....	89
Figure 5.26 Wind speed reduction graphs in oblique wind conditions for shelterbelts with width=0.5 height for incidence angles of 15°, 45° and 75° (Wang & Takle 1996:98-99)	90
Figure 5.27 Influences of shelterbelts on air temperatures (Robinette 1983a:36)	92
Figure 5.28 The effects of different porosity configurations and built windbreak structures on air flow and temperatures (Robinette 1983a:68-70)	93
Figure 5.29 Placing entrance and exit openings for airflow at right angles eliminates dead air pockets and improves ventilation (adapted from Robinette 1983a:115)	95
Figure 5.30 Placement of building clusters at an angle diagonal to that of the approaching wind increases overall ventilation (Robinette 1983a:114)....	95
Figure 5.31 In cool regions a shelterbelt placed one and a half to two times the height of a building upwind of that building combined with fenced enclosures on the south side will greatly reduce air infiltration and heat loss (Robinette 1983a:86)	96
Figure 5.32 When forced to locate building clusters perpendicular with the direction of the wind in cool regions, shelterbelts in combination with built windbreaks can significantly reduce air infiltration and heat loss (Robinette 1983a:89)	96
Figure 5.33 Different plan shapes afford different solar access possibilities for different climates (Napier 2000:7.2.1-7.2.7)	98
Figure 5.34 Different duplex plan shapes and orientations for solar access (adapted from Erley and Jaffe 1979:57).....	99
Figure 5.35 Planting design in section for optimal solar access control.....	100
Figure 5.36 Tree shadow template for a tree in winter and summer, used to determine optimum placement for solar access control	101
Figure 5.37 Allowing sunlight to be filtered by plant material, or reflected from another surface before entering a building, increases lighting quality and reduces glare	102
Figure 5.38 Different strategies to allow reflected and overhead sunlight into buildings (Lam 1986:76,144,148).	103
Figure 5.39 Suggested spatial arrangement of interiors of a solar home for optimum efficiency in sunlight use (Mazria 1979:91).....	104
Figure 5.40 Daylighting solutions when the view and sun are in opposite directions (Napier 2000:8.11.3, 8.12.1)	105

Figure 5.41 Diurnal variations in roof temperatures inside test structures (Nahar <i>et al</i> 1999:92).....	108
Figure 5.42 Surface temperatures of different building façades (Bonan 2000:106)	109
Figure 5.43 The use of vertical and horizontal built shade devices for different times of the day (Lam 1986:84-85)	110
Figure 5.44 Surface temperatures of soils covered with different materials (Wong <i>et al</i> 2003:358)	110
Figure 5.45 Section of contemporary sod roof construction (Thompson and Sorvig 2000:112).....	111
Figure 5.46 Temperatures of various surfaces of a Colorado, USA suburban neighbourhood measured on 17 July 1997 (Bonan 2000:106).....	112
Figure 5.47 Solar water heater cost comparison (Ward 2002:54)	114
Figure 5.48 Different irrigation zones to minimise unnecessary and ineffective residential garden water use (adapted from Robinette 1984:125,196)	116
Figure 5.49 Conceptual garden layout based on different irrigation zones (adapted from Robinette 1984:125).....	117
Figure 5.50 Ways by which water enters onto and leave residential properties (adapted from Morrow 1993:40)	119
Figure 5.51 Depressions in the landscape used to collect surface runoff (adapted from Waterfall, accessed 11-09-2003)	120
Figure 5.52 The choice between a flat and pitched roof does not influence the amount of surface available for rainwater harvesting (Waterfall, accessed 11-09-2003).....	123
Figure 5.53 Combination of water harvesting and runoff utilisation techniques for a single residence	123
Figure 5.54 Hypothetical water use of conventional household (Robinette 1984:165)	125
Figure 5.55 Reduced water use through partial re-use (Robinette 1984:166).	125
Figure 5.56 Further reduction in water use through utilisation of collected rainfall.....	126
Figure 5.57 Basic components of residential two-stage gray water purification system (Al-Jayyousi 2003:189).....	127
Figure 5.58 Section through residence illustrating courtyard and fountain combination to create cooler conditions in hot arid regions	128

List of tables

Table 1.1 Average annual percentage of the possible sunshine for selected cities (Neethling 1978:46)	11
---	----

Table 2.1 Apparent temperature as a function of relative humidity (Henderson-Sellers and Robinson 1986:332).....	28
Table 2.2 The human discomfort index (Weather Bureau 1987:10).....	29
Table 2.3 Wind chill equivalent temperatures (Weather Bureau, 1987:12).....	31
Table 3.1 The temperate climates and generalised typical characteristics (Gresswell 1979:84)	50
Table 5.1 Implications of density for sustainable housing – comparison of three paradigms (Edwards 2000:132).....	66
Table 5.2 Site orientation guidelines for the four main climate regions of the world (Keplinger 1978 as shown in Owens 1986:45)	69
Table 5.3 Time lag of heat flow through various construction materials (Strock and Koral 1965 as shown in Mazria 1979:345)	75
Table 5.4 Albedos, emissivities and thermal conductiveness of common elements in the landscape (Brown & Gillespie: 1995:49).....	106

List of abbreviations

ASLA: American Society of Landscape Architects Foundation

BTU: British thermal unit

CSIR: Council for Scientific and Industrial Research

DBSA: Development Bank of Southern Africa

DEAT: Department of Environmental Affairs and Tourism

DI: Discomfort index

DME: Department of Minerals and Energy

DWAF: Department of Water Affairs and Forestry

GWh: Gigawatt hours

IDRC: International Development Research Centre

ISES: International Solar Energy Society

kWh/m²: kilowatt hours per square metre

MW: megawatt

NBRI: National Building Research Institute

RH: Relative humidity

SABS: South African Bureau of Standards

SBAT: Sustainable building assessment tool

SEED: Sustainable Energy for Environment & Development Programme

SHI: Sustainable Homes Initiative

UN: United Nations

WHO: World Health Organisation

W/m²: Watt per square metre

Glossary of terms

Albedo: The ratio of reflected solar radiation to the total incoming solar radiation where both streams are measured across the complete wavelength range of solar radiation.

Built windbreak: A built structure such as a fence or wall that is designed and placed to reduce the speed of oncoming wind on its downwind or leeward side.

Climate/climatic region: A generic term used in this study to indicate any geographic area with common climatic characteristics.

Discomfort Index: A system used by weather services to determine how uncomfortable certain combinations of temperature and humidity are to humans, determined by the equation $(2 \times T) + (RH/100 \times T) + 24 = DI$ where: T = temperature in °C, RH = relative atmospheric humidity and DI = discomfort index.

Embodied energy: Energy associated with the production, transport and storage of materials in construction that is “hidden” and not directly associated with the building process itself.

Emissivity: The degree to which a real body approaches being a perfect absorber and emitter of radiation.

Energy efficiency: Using energy and the resources used in its production in ways that eliminate unnecessary or avoidable waste.

Life-cycle costs: The comparison of the capital expenditure used to create the system compared with the savings in money that arise from reduced fuel use.

Shelterbelt: A structure that is composed of plants and designed and placed to reduce the speed of oncoming wind on its downwind or leeward side.

Skyspace: The solar access zone or portion of sky north (in the southern hemisphere) of a collector that must remain unobstructed by objects that block solar radiation, in order for a solar collector to function optimally.

Sustainable development: Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Windchill factor: The process through which wind augments the convective heat loss through the skin, resulting in a temperature being perceived as being lower than the ambient atmospheric temperature. This phenomenon is especially pronounced under cold conditions.

Windbreak: A generic term used in this study to indicate both built windbreaks and vegetative windbreaks or shelterbelts.