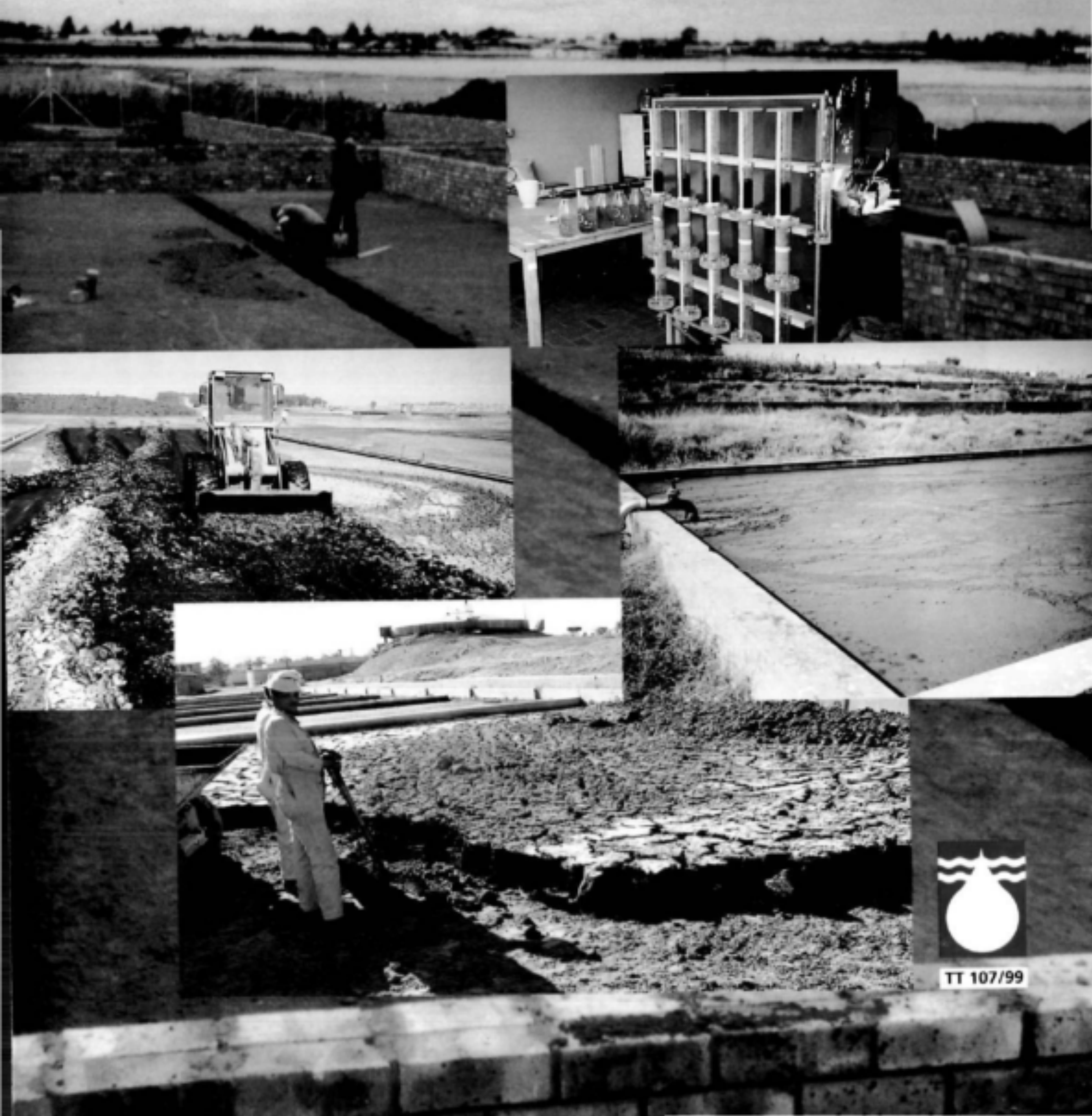
Guidelines for the Design and Operation of Sewage Sludge Drying Beds

AD Ceronio • LRJ van Vuuren • APC Warner



TT 107/99

GUIDELINES FOR THE DESIGN AND OPERATION OF SEWAGE SLUDGE DRYING BEDS

by

AD Ceronio

LRJ van Vuuren

APC Warner

Report to the

WATER RESEARCH COMMISSION

by

GFJ (Pty) Ltd

WRC Report No: TT107/99

Obtainable from

Water Research Commission
PO Box 824
Pretoria
0001

The publication of this report emanates from a project entitled: *Guidelines for the Design and Operation of Sewage Sludge Drying Beds* (WRC Project No 604).

DISCLAIMER

This report has been reviewed by the Water Research Commission (WRC) and approved for publication. Approval does not signify that the contents necessarily reflect the view and policies of the WRC, nor does mention of trade names or commercial products constitute endorsement or recommendation of use.

ISBN 1 86845 491 6

Printed in the Republic of South Africa

Beria Printers (012) 379-9095/6

EXECUTIVE SUMMARY

GFJ (Pty) Ltd were approached by the Water Research Commission and requested to compile guidelines for the design and operation of sludge drying beds in South Africa. The Commission had identified the need for guidelines after it became apparent that although South African conditions were, for the most, ideally suited to the use of this dewatering method, designers and operators had difficulty in optimising its use. An initial investigation indicated that the problem was due to a lack of information.

It was therefore decided to compile this guide in the following manner:

- identify fundamental work done by others that would have a relevance to this guide,
- complement this work with additional experimental work,
- translate the fundamental work into practical design and operational guidelines, and
- determine what the status of sludge bed design and operation is in South Africa, find the shortcomings and make suggestions toward remedying this, based on the first three steps.

It was found that characterising sewage sludge and predicting its behaviour is a complex matter that has been receiving continued scientific attention for quite some time. The work was however not nearing completion. It was decided not to delve too deeply into this, as it would be beyond the scope of this project.

An understanding of certain fundamentals involved in sludge dewatering is however required to design and operate the beds. This includes a realisation of the complex nature of sludge and how this influences the dewatering process. The entire process can be divided into two part, namely drainage and drying (evaporation). Drainage would not normally take up a large portion of the total drying time but could account for more than 75% reduction in the water content of the sludge. The drying time is normally considerably longer.

Mathematical equations and models are found in literature describing both these steps. In general these models are not suitable for use in design, as samples of the sludge are required for analysis and the models contain variables that effectively calibrate the model, such as specific resistance to filtration (R_c) and compressibility (σ). Walski (1976) proposed a model that is less dependent on such variables. Furthermore the Walski model takes varying climatic conditions and operational procedures into account which makes this a valuable design and operational tool.

The Walski model does however also need inputs from analysis on existing sludges. The experimental work done during the compilation of this guide was aimed at providing the designer with design estimates for these parameters. It was found that a relationship exists between solids concentration at the time of application (S_0), the solids concentration after drainage (S_1) and the solids load (SL) applied to the bed.

Other work done concentrated on verification of parameters or ratios describing the rate of evaporation from sludge and also the amount of water retained by the sludge should it be subjected to rainfall.

The result of the experimental work done as well as information obtained from the literature was used in the compilation of design guidelines for sludge drying beds.

Questionnaires were sent out to 536 local authorities, from which there were 121 responses. Thirty of these containing the most useful information were selected. Using these 30 responses, and from site visits and interviews held with operators of sewage treatment plants, it was found that the main problem areas were:

- a lack of formal training of operators, which leads to operational errors such as overloading,
- insufficient or too much bed capacity, as a result of poor design guidelines, and
- low productivity and other labour difficulties.

These interviews were followed up by discussions with designers, which led to similar conclusions.

Based on the literature survey, fundamental work, questionnaires, site visits and interviews, a number of design and operational guidelines could be compiled. The most important conclusions from this study indicate that:

- designs must be based on site and plant specific variables;
- designs should be based on worst-case scenarios in terms of climatic conditions unless alternative dewatering procedures were available; and
- plant operators should try to optimise operation through experimentation - a log of activity and statistics on the beds' performance are crucial in this regard.

It is recommended that future research on sludge drying beds should concentrate on further verification of the Walski parameters and more detailed guidelines on the media used in sand beds.

ACKNOWLEDGEMENTS

This work was carried out under the guidance of the Water Research Commission who also funded the project. The Steering Committee comprised the following members:

- Mr J Bhagwan - Water Research Commission - Chairman
- Dr NP Mjoli - Water Research Commission
- Mr C Chapman - Water Research Commission
- Dr S. Mitchell - Water Research Commission
- Mr GB Saayman - Pretoria City Council
- Mr RW Wakefield - Port Elizabeth City Council
- Mr C Olivier - Durban Metro - Waste Water Management
- Mr CS Crawford - Department of Water Affairs and Forestry
- Mr GF Hefer - Department of Water Affairs and Forestry
- Mr ME Mosia - Water Research Commission - (Committee Secretary)

The project team wish to thank the members for their valuable input during the course of this project.

It is also necessary to thank a number of institutions, municipalities, town engineers and plant operators for assisting the project team during their site visits and experimental work. These include Pretoria, Centurion, East London, Ermelo, Standerton, Bethal, Babelegi and Erwat, amongst others.

Following on the questionnaires that were sent out a word of gratitude is extended to the respondents for taking the time to complete the forms as well as for their assistance in the telephonic interviews that followed. There were more than 120 respondents and this unfortunately makes the list too extensive to record, but it does not diminish the project team's gratitude.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

Page

CHAPTER 3 : THE WALSKI MODEL

CHAPTER 4 : LABORATORY AND FULL-SCALE TESTING

CHAPTER 5 : THE CURRENT SITUATION IN SOUTH AFRICA

CHAPTER 6 : GUIDELINES FOR DESIGN

TABLE OF CONTENTS (CONTINUED)

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

%m	=	moisture content (%)
%W	=	percentage water
μ	=	dynamic viscosity (poise)
ρ	=	density of sludge (kg/m^3)
σ	=	coefficient of compressibility
a	=	surface area of filtration (cm^2) (resistance to filtration)
a	=	evaporation ratio from sludge relative to clean water
A	=	bed area (m^2)
aE-bR	=	effective evaporation (cm/mo)
A_T	=	*total bed area (m^2) based on total dewatering time* T(d)
A_T/q_s	=	specific bed area ($m^2/m^3.d$)
b	=	slope from t/V vs. V plot (resistance to filtration)
b	=	fraction of R absorbed by sludge (Walski, 1978)
BLR	=	bed loading rate ($kg/m^2.a$)
c	=	weight of solids per unit volume of filtrate (kg/m^3)
E	=	evaporation from clean water (cm/mo)
f	=	weight of solids per unit volume of filtrate
f*	=	weight of solids per unit volume of filtration ($g/cm^2.s^2$)
g	=	gravitational acceleration (m/s^2)
GBL	=	gross bed load (kg/m^2)
H	=	depth of sludge cake at t
h_0	=	effective depth of water at t_0
H_0	=	depth of sludge bed at t_0 (cm)
h_1	=	effective depth of water at t_1
H_1	=	depth of sludge bed at t_1 (cm)
h_2	=	effective depth of water at t_2
H_2	=	apparent depth of sludge bed at t_2 (cm)
H_d	=	variable depth of drainage (cm) ($t_0 - t_1$)
H_s	=	variable depth of sludge bed (cm) ($t_0 - t_1$)
h_w	=	effective depth of water
H_w	=	effective depth of water
m	=	media factor
M_0	=	moisture content (%) before rain
NBL	=	nett bed load ($kg/m^2.d$)
ρ_s	=	density (kg/m^3)

LIST OF SYMBOLS (CONTINUED)

Q	=	volumetric sludge flow rate (m^3/d)
Q_c	=	current raw sewage flow rate (m^3/d)
Q_d	=	design raw sewage flow rate (m^3/d)
q_s	=	volume of sludge to drying beds (kℓ/d)
R_c	=	specific resistance at head h (resistance to filtration)
R	=	rainfall typical wet month cm (month) (Walski, 1978)
R_c	=	specific resistance to filtration (m/kg)
R_d	=	daily rainfall (cm)
S	=	mass solids (kg)
S_0	=	% solids by mass at t_0
S_1	=	% solids by mass at t_1
S_2	=	% solids by mass at t_2
S_c	=	% solids of sludge cake (resistance to filtration)
SL	=	solids load (kg/m^2)
S_s	=	% solids of sludge (resistance to filtration)
S_w	=	percentage solids at H_s
T	=	$t_1 + t_2$ (total dewatering time)
t_0	=	zero time when bed is loaded
t_1	=	drainage time (d)
t_2	=	evaporation time (d)
W	=	mass of water
% W_d	=	percentage water drained from sludge
ΔP	=	pressure loss across a sludge cake (dynes/cm^2) or (N/m^2)

CHAPTER 1

INTRODUCTION

1.1 RELEVANCE OF SLUDGE DRYING BEDS

Sewage sludge drying beds are commonly used throughout the country and across the world as an effective method of sludge dewatering. The beds may or may not be preceded by a sludge thickening step. Sludge taken from the beds is normally dumped, but can also be treated further to deliver a product of beneficial use. Although alternatives to sludge beds, such as belt presses, have been introduced at some large plants, sludge beds will remain a viable option for designers and operators because of their relative ease of operation and relatively low running cost. This is particularly true for smaller plants. For larger scale plants, mechanical hauling rather than manual removal is preferred. For this purpose concrete lined beds without filter media are often used.

Sewage sludge drying beds are used with varying degrees of success in South Africa. Their success depends mainly on climatological factors, type of sludge, sludge loading rates and operating efficiency. Haseltine (1951) summarizes the status quo in stating that drying beds are the most common means of drying sewage sludge, but despite this fact no phase of sewage treatment has received less scientific attention or less mention in operating reports. This lack of scientific approach is evidently due to the large number of variables to be considered and include:

- the source and type of original sludge;
- the extent of digestion, age, composition and concentration of the sludge;
- the method of sludge transfer - gravity, type of pumps, etc, and
- the presence or absence of coagulants.

Generally the conditions in South Africa are ideally suited to the use of sludge drying beds. Factors that contribute are high evaporation rates, fairly low rainfall rates, the availability of space and also a large available labour force. Despite this a large number of plant operators prefer not to make use of their beds and dispose of their sludge by means of irrigation and in lagoons. Reasons given for this include poor design, climatological complications, labour difficulties, unsuitable sludges and other operational difficulties. Activated sludges of poor stability are particularly problematic in terms of environmental aspects such as offensive odours and leachates.

The designs currently used in South Africa are based mainly on past experience and occasionally use is made of internationally sourced literature which in most cases has limited relevance to South African conditions. Furthermore limited attention is given to varying climatic conditions. This situation is aggravated by the fact that research that has been done on the fundamental aspects of the actual sludge drying processes is seldom translated into practical design and operational guidelines. A result of this is that plant operators are often not properly trained in the operation and optimisation of the beds.

1.2 OBJECTIVES OF THE GUIDE

Roughly one fifth of the capital cost of a new sewage treatment plant can be attributed to sludge drying beds. Despite this, very little local research is accessible to designers, limited design guidelines are available and even less is available to guide the operator.

It is the purpose of this guide to attempt to address this situation. This guide contains an evaluation of fundamental research work that has been done on the topic. It also defines and discusses some fundamental principles that would assist in the design and operational stages. Models proposed for the design of sludge beds are investigated and practical suggestions are made towards the physical design and detailing of the beds. Furthermore suggestions are made towards the optimisation of bed operation.

1.3 PROCEDURES FOLLOWED AND PRESENTATION OF INFORMATION

It has been necessary to include some fundamental experimental work along with practical guidelines in this report due to the fact that very little data was available during the compilation of this guide. This work is included in this guide as it leads to an understanding of the basic mechanisms that underlie the (essentially) simple requirements for the successful design and operation of sludge drying beds.

This guide begins by discussing the fundamentals involved in sludge drying (Chapter 2). From these fundamentals flow a number of drying models which can be utilized in the design of sludge beds. Some basic experimental work was done during the compilation of these guidelines to confirm certain parameters used in a selected model and also to give design estimates for certain prime parameters in this model. These are contained in Chapters 3 and 4.

In order to determine the extent to which design and operation influence performance a number of visits were made to treatment plants where interviews were held with the various operators and designers. Furthermore a questionnaire was sent to more than 520 local authorities. The conclusions drawn from these interviews and questionnaires are presented in Chapter 5.

A chapter on design is also presented. This discusses the basic points that should be considered during the design process and covers aspects ranging from sizing to detailing. As climate plays a key role in the drying process, a study was also made of climatological variations throughout South Africa. Some references are made to this in the design chapter. In addition to this the various existing design models are presented in this chapter to compare and discuss the results.

The operation of a sludge bed contributes as much to its success as does the design. A chapter on operational and maintenance requirements as well as on optimisation is included.

The Guide concludes with a chapter that summarizes further research needs.

CHAPTER 2

FUNDAMENTALS OF SLUDGE DRYING

2.1 INTRODUCTION

In order to design and operate sludge drying beds optimally it is important to have an understanding of the fundamentals involved in sludge drying. These fundamentals are discussed extensively in published papers, reports, case studies, etc. Some of these sources reflect a highly fundamental approach backed by laboratory and pilot-scale testing. Others are more empirically based with the focus on particular design aspects or problem areas.

For the purpose of this guide the information most relevant to design has been selected and summarised. The gross overlap of a large number of parameters and aspects involved complicates the presentation of the reviewed literature under categories and subsections. The fundamentals are presented under the following main headings:

(i) Sludge characteristics
(ii) Dewatering mechanisms
(iii) Design methods and criteria for sizing of beds.

2.2 SLUDGE CHARACTERISTICS

Dewaterability of sludges depends on a number of characteristics such as physical, chemical or biochemical properties. These include the water (moisture) content which is present in various forms. The original source of the sewage and the treatment processes also determine the type of sludge and its characteristics.

From a practical view point the water content and loading depths are of overriding importance. From a theoretical viewpoint the resistance to filtration, and compressibility are the major parameters involved.

2.2.1 Moisture content

In environmental engineering the term *water content* (%W) is usually associated with large amounts of water and is defined as the mass of water divided by the total mass (solids plus liquid). The term *moisture content* (%M) refers to much smaller amounts of water and is defined as the mass of water per mass of dry solids. The term *water content* is convenient during the drainage and early stages of sludge drying, whereas the term *moisture content* is more convenient during the later stages of drying (Adrian,1978). *Solids content* is defined as the mass of solids divided by the total mass. The term *moisture content* is generally also used in the literature for water content as defined above. Thus solids content plus water content is unity. In mathematical terms:

$$\%W = \frac{W}{S+W}100 \qquad \text{.......... 2.2.1(a)}$$

Where %W is the percentage of water,
W is the mass of the water, and
S is the mass of the sludge solids

and further

$$\%M = \frac{W}{S} \times 100$$

$$\%S = (100 - \%W) \qquad \text{.......... 2.2.1(b)}$$

%W and %M are also related as follows:

$$\%W = \frac{\%M.100}{\%M + 100}$$

$$\%M = \frac{\%W.100}{100 - \%W} \qquad \text{.......... 2.2.1(c)}$$

2.2.2 Types of moisture

Various disciplines use different nomenclature for the types of water associated with sludges (Adrian, 1978). On the basis of experimental data, Smollen (1988) distinguished between four categories of municipal sludge moisture content. These are illustrated schematically in Figure 2.2.2. and are briefly expanded upon below.

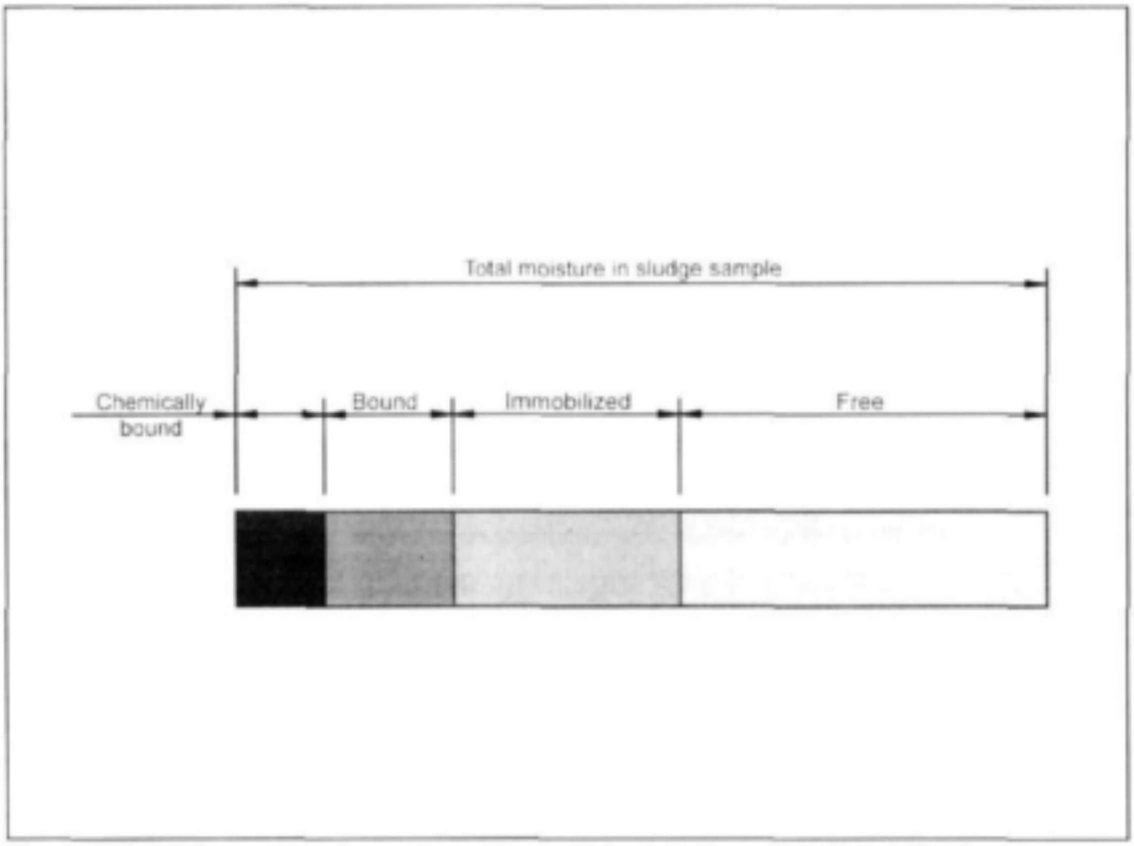


Figure 2.2.2: Types of moisture found in municipal sludges (Smollen, 1988)

- Free moisture - minimally bound to solids, removable by gravity drainage.
- Immobilised water - floc entrapped water characterised by low binding energy, removable by mechanical methods (vacuum, centrifugation or pressure filtration).
- Bound moisture - strongly absorbed onto individual sludge particles, removable by processes such as electro-osmotic and thermal drying processes.
- Chemically bound moisture - bound by strong chemical bonds, removable by thermal drying at temperatures above 105°C.

Smollen concluded that low immobilised moisture content was usually associated with a short drying time, and that a granular appearance of the dried cake calls for the use of drying beds. On the other hand a high immobilised moisture content and cohesive sludge cake appearance, calls for mechanical dewatering methods.

For the purposes of this guide only two types of water (moisture) will be considered. These are:

- water removed by gravity (free or drainable water) and
- water removed by evaporation (bound water).

The relationship of R_c to head is empirically related as follows:

$$R = R_c \left(\frac{h}{h_c} \right)^{\sigma} \qquad \text{. . . . . 2.2.4(c)}$$

Where R = Specific resistance at head h

R_c = Specific resistance at head h_c

σ = Coefficient of compressibility.

Values for R_c and σ derived from the literature are listed in Table 2.2.6(a).

Table 2.2.4 (a) : Values for R_c and σ derived from literature

Types of sludge	% Solids	Rc s^2/g or m/kg	σ	P	Reference
Primary anaerobic digested sludge	9.5	$2{,}6 \times 10^{10}$ (s^2/g)	0.68	38.1 cm Hg	Nebiker
Anaerobic digested mixed with activated sludge	3.6	$4{,}8 \times 10^{10}$ (s^2/g)	0.66	38.1 cm Hg	Sanders
Anaerobic digested mixed with trickling filter sludge	6.1	$8{,}25 \times 10^{9}$ (s^2/g)	0.9	38.1 cm Hg	Quon
Aerobically digested sludge	4.5	$1{,}15 \times 10^{9}$ (s^2/g)	0.97	-	Cummings
Anaerobically digested sludge	-	$100\text{-}480 \times 10^{12}$ (m/kg)	0.5-0.8	-	Adrian

Smollen (1986) also reported R_c values from different sources in South Africa at 49 kPa differential pressure. The values are summarised in Table 2.2.4(b).

Table 2.2.4(b) : Values for R_c from different sources in South Africa (Smollen,1986)

Sludge description	R_c-values (10^{12} m/kg)
Primary sludge	(100-150), (6-230), (60-200), 215, 14, 174, 19, (100-300)*
Waste activated sludge	(1-8), (3-20), 2,6-28), (0,6-13,4), 4,3 , 40
DAF waste activated sludge	(10-124), (77-420), (18-24), 29, (40-120)*
Primary anaerobic digested sludge	(32-388), 38, 58, (30-300)*
Anaerobically digested primary and activated sludge	(400-2600), (200-620), 138
Aerobically digested sludge	(2,2 - 5,5)
Anaerobically digested humus	64
*USA EPA data	

Anaerobically digested mixtures of primary and activated sludge show the highest R_c-values. Good intermediate filtration properties of waste activated sludges are indicated, particularly those produced by extended aeration plants. The wide variations as listed above are of little design significance but broadly indicate better dewaterability of aerobically digested sludges.

2.2.5 The effect of solids concentration on R_c

Theoretically R_c should be independent of solids concentration. This has however been found not to be so in practice. For anaerobically digested sludge Smollen (1986) found an increase in R_c with a decrease in solids concentration. The opposite appears to apply to activated sludges.

2.2.6 Other factors affecting R_c

Other factors that affect R_c include particle size distribution, biopolymer formation and compressibility (Smollen, 1986). When a sludge contains fine particles, R_c is effected by the blinding by the sludge cake on the support media. High blinding was recorded with primary and anaerobic digested sludges while moderate levels of or no blinding was found with activated sludges.

The quantity of high molecular polymers was found to correlate with dewatering characteristics in that dewatering improves when the dissolved bio-polymers are removed from the solution phase. According to Pitman (1975) deterioration in dewaterability of activated sludge is caused by mobile micro-organisms that maintain fine particles in the liquid phase. He suggested that filtered effluent suspended solids could give a good indication of sludge dewaterability.

2.3 DEWATERING MECHANISMS

As discussed earlier in this chapter, two dewatering mechanisms are of primary importance in sludge drying beds. The first is the drainage mechanism and the second is evaporation. During the drainage phase the sludge would, under normal circumstances, lose the bulk of its water. This phase can last from several hours to a number of days depending on the characteristics of the particular sludge. The moisture remaining in the sludge after this phase is then removed by evaporation to a level where the sludge can be removed from the bed.

2.3.1 Gravity drainage

Various literature sources were consulted and the models reported for the determination of drainage times were compared for uniformity in terms of units used and particularly also the terms effected by the compressibility factor σ. It was found that various authors have adopted, with minor alterations, a model proposed by Adrian (1978). These authors include Lo (1971), Marklund (1990), and Palmer (1985). The fundamentally derived model is reproduced in equation 2.3.1 (a).

$$t = \frac{\mu\ R_c f}{\rho g\ (H_c)^{\sigma}\ (\sigma+1)} \left[\frac{H_0^{\sigma+1}}{\sigma} + H^{\sigma+1} - \frac{\sigma+1}{\sigma} H_0 H^{\sigma} \right] \qquad \ldots\ldots\ldots\ 2.3.1(a)$$

This equation is based on c.g.s. units where :

t	=	time (s) (drainage)
μ	=	viscosity (g/s.cm)
R_c	=	specific resistance (s^2/g) at reference pressure H_c (cm)
ρ	=	density (g/cm^3)
g	=	gravitational acceleration (cm/s^2)
H_0	=	depth of sludge (cm) at t_0
H	=	depth of cake (cm) at t

and also equation 2.3.1(b):

$$f = \frac{\rho g}{\left(\frac{100}{S_0} - \frac{100}{S_1} \right)} \qquad \ldots\ldots\ldots\ 2.3.1(b)$$

Where S_0 is the percentage sludge solids prior to drainage and S_1 the percentage sludge solids after drainage has been completed. Assuming 100/S_1 is relatively small, equation 2.3.1(a) can be simplified to result in equation 2.3.1(c):

$$t = \frac{\mu\ R_c S_0}{100\ (H_c)^{\sigma}\ (\sigma+1)} \left[\frac{H_0^{\sigma+1}}{\sigma} + H^{\sigma+1} - \frac{\sigma+1}{\sigma} H_0 H^{\sigma} \right] \qquad \ldots\ldots\ldots\ 2.3.1(c)$$

The denominator 1/(σ+1) can be included into the second half of equation 3.2.1(a) giving equation 2.3.1(d):

$$t = \frac{\mu\, R_c S_0 S_1}{100(S_1 - S_0) H_c^{\sigma}} \left[\frac{H^{\sigma+1} - H_0^{\sigma+1}}{\sigma+1} + \frac{H_0^{\sigma+1} - H_0 H^{\sigma}}{\sigma} \right] \qquad \text{.......... 2.3.1(d)}$$

Adrian (1978) suggested the use of equation 2.3.1(c) for wastewater sludges where $S_1 >> S_0$, but for water treatment sludges, a modified equation 2.3.1(d) is suggested which includes amongst others a media factor. This modification does, however, not fall into the scope of this guide and is therefore not included here.

The fundamental problem with this model in terms of its use as a design tool is that a sample of the sludge is required to determine the values for R_c and σ. This is, however, impossible *during the design phase of a new sewage treatment plant. Should the drainage time be* required for the extension of an existing plant, it would be much easier, and more accurate, to measure the drainage time from existing beds than to calculate it.

Of importance to note is that drainage time is relatively short but accounts for a major portion of the water removed from sludge.

2.3.2 Evaporation from sludge

The drying of sludges by evaporation is based on a large number of parameters which are complexly related and associated with environmental conditions (e.g. humidity, temperature, wind velocity, etc.), and operational aspects (e.g. depth of loading etc.) For the purpose of this guide a few of the more important definitions or concepts are briefly outlined below. A typical drying curve is shown in Figure 2.3.2.

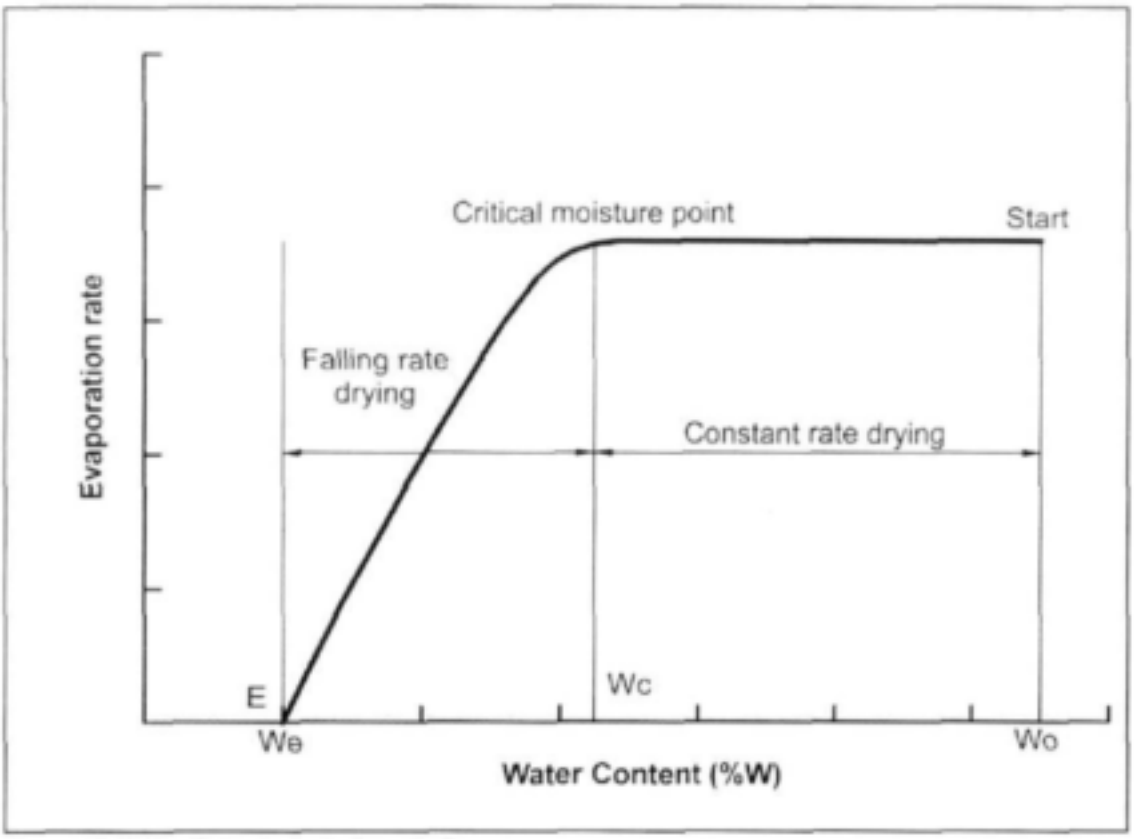


Figure 2.3.2 : A typical sludge drying curve

- Constant rate drying period

  Sludge dewatering by evaporation occurs in two distinct phases. The initial phase is known as the constant rate drying period (W_o to W_c). Evaporation loss continues at a constant rate until the free surface moisture is exhausted and can no longer be replenished by the internal transport of water to the sludge surface.

- Decreasing rate period / Non-linear / Falling / Declining

  Further evaporation then occurs in the period known as the falling rate or non-linear or declining rate period (W_c to W_e). The falling rate phase may or may not be linear with time and depends on the nature of the sludge.

- Critical moisture

  This marks the transition from the constant to the falling rate period and is influenced by dosing depth amongst other factors.

- Free water surface

  Water evaporates at a higher rate from a free water surface. Since the major portion of the total drainage is completed rather quickly in relationship to total dewatering time, it would appear that the constant rate drying period would be of short duration. It is probable that most of the total sludge moisture loss is the result of drainage and the falling rate of evaporation losses (Jennet and Harris, 1971).

- Evaporation ratio

  This is the ratio between water evaporated from a free water surface relative to additions where the critical moisture content has been reached. This guide uses Walski's (1978) nomenclature and denotes this by the variable "a".

Marklund (1990) conducted experiments on the evaporation from small bodies of water and sludges under controlled humidity, temperature and wind conditions. The most important findings from this work are reproduced below:

"Evaporation from two pilot sludge beds was studied in open air test lasting four months. One similar bed was tested in a controlled environment. The results showed that above a critical moisture content between 600 and 1100%, evaporation from sludge equals the evaporation from a free water surface. Below the critical moisture level the rate decreased rapidly." (Note: 600 to 1100% moisture respectively represents 15 to 8% solids indicating that a factor for evaporation from sludge only becomes relevant for concentrations of > 10% solids.)

2.4 DESIGN METHODS AND CRITERIA FOR SIZING OF BEDS

Various authors have proposed several models to be used directly in the prediction of sludge drying and bed sizing. The most relevant models are discussed in the following paragraphs.

2.4.1 Swanwick's methods

2.4.1.1 Swanwick's empirical formulation (Adrian, 1978)

Pilot plant studies in England on sludge dewatering yielded the conclusion that specific resistance (Rc) is related to bed loading ($kg/m^2.a$). A plot of Swanwick's data (Fig. 2.4.1.1) is described by the following equation:

$$BLR = \frac{10^7}{R_c^{0,5}} \qquad \text{.......... 2.4.1.1}$$

Where BLR represents the bed loading rate ($(kg.a)/m^{-2}$) and R_c (s^2/g) specific resistance at 36,9 cm mercury.

Although it is quite possible that a relationship exists between bed loading and specific

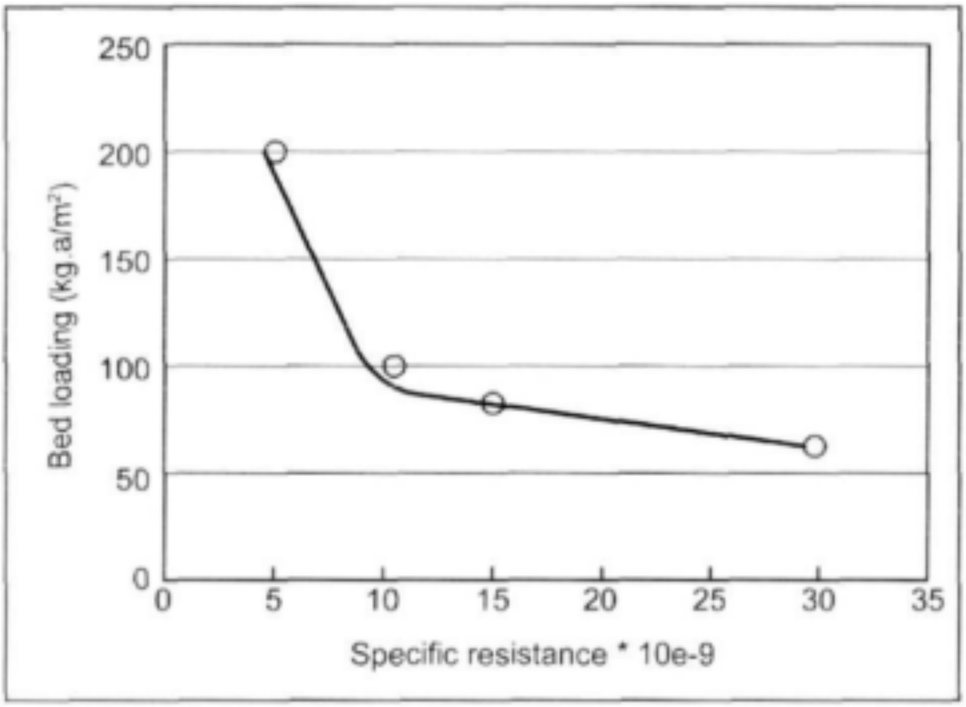


Figure 2.4.1.1 : Swanwick's data (Adrian, 1978) showing the relationship between bed loading and specific resistance (R_c)

resistance it is highly improbable that this relationship is precisely described by Swanwick's formulation (Adrian, 1978). Other factors which are related to bed loading and unrelated to specific resistance (such as evaporation) most certainly play a considerable role in the dewatering of sludge.

2.4.1.2 Graphical method by Swanwick (Adrian, 1978)

Based on the assumption that moisture is evaporated from sludge at a rate that can be related to the evaporation rate of free water by a constant, and that only a portion of rainfall on a bed is retained in the sludge, Swanwick proposed a graphical method to determine sludge drying time and the bed area required. The method, as proposed by Swanwick, is set out below (Adrian, 1978):

1. Fill a one-inch diameter glass tube with a sand base with sludge to a depth of 12 to 18 inches (305 to 460 mm).
2. Allow complete drainage of water from sludge (This will usually occur in a period of 12 to 48 hours depending on moisture content and sludge characteristics).
3. Remove the drained sludge plug and measure the moisture content after drainage.
4. Place the plug in an exposed dish for evaporation to occur. Periodically check the plug until a desired terminal moisture content is reached.
5. Measure the remaining moisture content. The difference in moisture content between steps 3 and 5 is the water to be evaporated.
6. From local meteorological records, determine the annual evaporation rate and annual rainfall rate.
7. Plot a cumulative plot of 0,75 times summation of evaporation vs. month and 0,57 summation of rainfall vs. month (This is based on experimental evidence that the average evaporation rate from wet sludge is 75% that of a free water surface, and that 43% of the rainfall is drained through the cake leaving 57% to be evaporated).
8. Prepare an overlay by month, indicating the total length of time a sludge discharge to a bed must be held for evaporation of any rainfall plus the remaining moisture calculated from step 5.
9. Prepare a tabulation of the total bed area required for each month. (The required area will increase during the wet periods of the year.)
10. The design requirement will be the maximum computed in step 9.

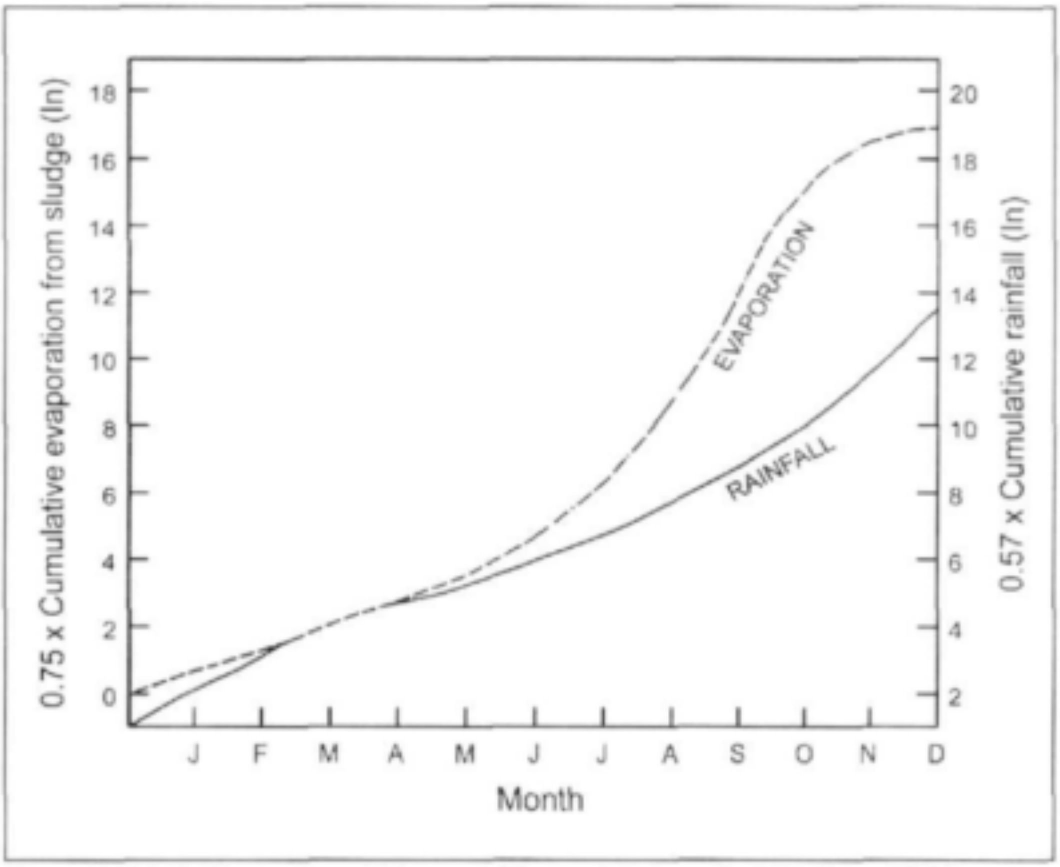


Figure 2.4.1.2: Illustration of Swanwick's graphical method (Adrian, 1978)

2.4.2 Haseltine empirical design equations (1951)

Haseltine (1951) pointed out that although sludge beds were in common use they had not received a sufficient amount of scientific attention and that this could be due to the large number of variables involved. The result of this was that the performance of sludge beds was measured crudely.

The most commonly used units were:

(i) number of fillings per year

(ii) cubic yards of wet sludge drawn per year

(iii) pounds of solids applied per ft^2 per year

Haseltine introduced a more logical concept, i.e. mass of solids applied per area per period (say 30 days) of actual bed use. This concept was named Gross Bed Loading (GBL). For example, if sludge containing 5% of solids is applied 0,3 m deep and removed after 40 days, the GBL per month would be calculated as follows:

$$GBL = \frac{\rho.H_0.S_0.Period\ of\ evaluation}{T}$$

$$GBL = 1000\frac{kg}{m^3}\ x\ 0,3m\ x\ 5\%\ x\ \frac{30\,days}{40\,days} \qquad \ldots\ldots\ldots\ 2.4.2(a)$$

$$GBL = 11,25\,kg\ per\ 30\ days\ /m^2$$

where ρ = sludge density (assumed as 1000 kg/m^3)

H_o = initial sludge application depth (m)

S_o = solids concentration during application (%)

T = total dewatering period (days)

In order to take into account the variable solids content of the sludge at the time that the sludge is removed, a second concept "Net Bed Loading" (NBL) was introduced which was defined as:

$$NBL = GBL.S_2\ /\ 100 \qquad \ldots\ldots\ldots\ 2.4.2(c)$$

Here NBL was multiplied by the percentage solids concentration of the sludge at the point of sludge removal (S_2).

Records of 1 to 14 years for different plants (winter months excluded) were used to calculate the various plants' GBL and NBL values. The sludges included primary sludge, chemically precipitated sludge, primary and humus sludge, primary and activated sludge, digested in Imhoff tanks, and heated or unheated single- and two-stage digesters and applied in various depths to open or glass-covered beds.

Plots of these results showed the following linear relationships:

$$GBL = 0,96\,S_0 - 1,75$$
$$NBL = 0,35\,S_0 - 0,52 \qquad \ldots\ldots\ldots\ 2.4.2(d)$$

where GBL is in pounds of solids per ft^2 per 30 days of service and NBL is as defined in equation 2.4.2 (c).

These equations are purely empirical and at best relate to annual averages over a wide geographical area with numerous climatic variations. Expressed in metric units (($kg/m^{-2}.d$) equation 2.4.2 (d) becomes:

$$GBL = 0{,}157\,S_0 - 0{,}286$$
$$NBL = 0{,}057\,S_0 - 0{,}082 \qquad \ldots\ldots\ldots\ldots\ 2.4.2(e)$$

Vater (Adrian, 1978) analysed the same data used by Haseltine and found that an exponential curve could better represent the data points. This equation for GBL is presented in metric units as:

$$GBL = 0{,}033\,S_0^{1.6}\ (kg/m^2.d) \qquad \ldots\ldots\ldots\ldots\ 2.4.2\ (f)$$

The curve by Vater seems more realistic since it goes through the origin whereas Haseltine's straight line does not (Figure 2.4.2).

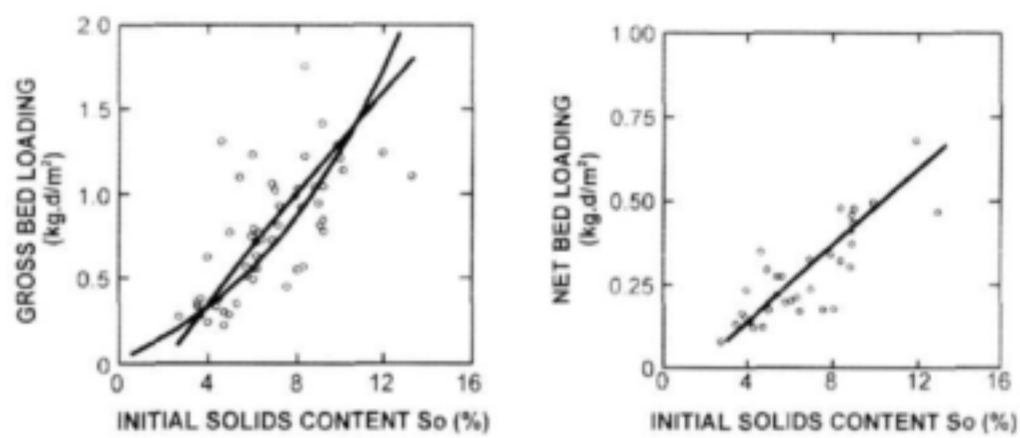


Figure 2.4.2 : Relationship of GBL and NBL to S_0 respectively

Haseltine's empirical equations have been used for dimensioning of sludge drying beds but these formula do not apply to old thoroughly digested or "dead" sludges.

2.4.3 Typical WPCF standards for design

The oldest and still most commonly used design tools used are the "area-per-load" or the "area-per-capita" guidelines which have been published in a number of references. Table 2.4.3 represents guidelines of this type that were published by the WPCF (Walski, 1976). These guidelines normally do not explicitly take account of any variation in climatic conditions and normally are based on past experience by the authors. The guidelines normally suggest a broad range of application rates from which the designer must work based on what he perceives the climatic conditions, amongst other variables, would allow.

Table 2.4.3 : Typical WPCF standards for design (Walski, 1976)

Sludge Type	Square Feet per Capita	
	Open Beds	Covered Beds
Primary digested	1,0 - 1,5	0,75 - 1,0
Primary and humus digested	1,25 - 1,75	1,0 - 1,25
Primary and activated digested	1,75 - 2,5	1,25 - 1,5
Primary and chemically precipitated digested	2,0 - 2,5	1,25 - 1,5

2.4.4 Mathematical model by Adrian (1978)

The research programme followed by Adrian (1978) was developed to examine sludge dewatering by both theoretical and experimental work. Its various components include formulation of mathematical models for sludge drainage and drying, preparation of input data for mathematical models, validation of simulation experiments, and analyses of the outputs generated by simulation so as to prescribe an optimum system design.

Derivations of the mathematical formulae are highly complex and require statistical inputs of a large number of parameters, e.g.:

- specific resistance and coefficient of compressibility
- filter media factor
- constant and declining drying rates
- critical moisture content
- evaporation ratios
- effect of rainfall (ponding and mixing models), etc.

For practical purposes this model is considered too laborious. However, this comprehensive report provided useful supporting information and references that were consulted in the development of this guide. A particular effort was made to interpret rainfall absorption data (Section 4.5).

2.4.5 Mathematical model by Walski (1976)

This model is essentially based on the Swanwick method which takes into account climatic variations amongst other variables. Bed area is calculated from the equation 2.4.5(a):

$$A_T = \frac{1{,}60\,Q}{H_0}\left[t_1 + \frac{30\,H_0 S_0}{aE - bR}\left(\frac{1}{S_1} - \frac{1}{S_2}\right)\right]\ sq.ft \qquad \text{.......... 2.5.4(a)}$$

where	A	=	Surface area in ft^2
	Q	=	Volumetric sludge flow (US gpd)
	H_0	=	Sludge loading depth (in)
	S_0	=	Initial % solids
	S_1	=	% solids after drainage time t_1
	S_2	=	% solids after evaporation time t_2

$$t_2 = \frac{30\,H_0 S_0}{aE - bR}\left(\frac{1}{S_1} - \frac{1}{S_2}\right) \qquad \text{.......... 2.5.4(b)}$$

where effective evaporation = aE - bR (in)

with	E	=	clear water evaporation rate (in/month)
	R	=	rainfall in wet month (in/month)
	a	=	correction factor for evaporation from sludge = 0,75 (Swanwick, 1964)
	b	=	fraction of rain absorbed by sludge = 0,57 (Swanwick, 1964)

In order to determine the drainage time (t_1) it is again required that the sludge be available to conduct some experimental work. The model is, however, a simple one which is easily applied and the information required is normally readily available. This model was therefore selected for a more detailed assessment for the purpose of using it as a final design tool. This is discussed in detail in Chapter 3.

CHAPTER 3

THE WALSKI MODEL

3.1 GENERAL

In this section the mathematical formulation and significance of the relevant parameters of the Walski model (Walski, 1976) are described. The Walski model was chosen as the model of preference in this guide because it makes provision for the most important variables. It is also not "run specific" but rather gives a general or average result which would be more suitable for use in design and since it is fairly simple it would find general acceptability in day-to-day use.

The original model as published (Walski, 1976) is expressed in terms of US gallons and Imperial units but these have been converted to metric units for the purpose of the Design Guide.

Application of the Walski model is essentially aimed at estimating the total bed area (A_T) for dewatering a daily production of sludge (q_s) at a bed loading depth (H_0) and total dewatering time (T), i.e.:

$$A_T = \frac{q_s}{H_0} T \qquad \text{3.1(a)}$$

In this regard an estimate of T is the main feature of the model which implicitly includes solids concentration and effective evaporation parameters as well as drainage time t_1. This is the time it takes for the sludge to lose its free water through drainage.

In metric form the Walski model is formulated as follows:

$$A_T = \frac{100.q_s}{H_0}\left[t_1 + \frac{30 H_0 S_0}{aE - bR}\left(\frac{1}{S_1} - \frac{1}{S_2}\right)\right] \qquad \text{3.1(b)}$$

The symbols have the following meanings:

A_T	:	total bed area (m^2)
q_s	:	sludge production (m^3/d)
H_0	:	bed loading depth (cm) at t_0

t_1	:	gravity drainage time (d)
		(to be determined experimentally by laboratory analysis)
t_2	:	evaporation time (d)
S_0	:	% solids concentration at t_0
S_1	:	% solids concentration at t_1
S_2	:	% solids concentration at t_2
R	:	monthly rainfall (cm)
E	:	monthly evaporation (cm)
a	:	factor for evaporation from sludge relative to clean water
b	:	rainfall absorption factor by sludge
aE-bR	:	effective evaporation (cm/month)
T	:	total dewatering time (t_1 + t_2 days)

The variable t_2 is expressed as:

$$t_2 = \frac{30 H_0 S_0}{aE - bR}\left(\frac{1}{S_1} - \frac{1}{S_2}\right) \qquad \text{3.1(c)}$$

The Walski model is essentially developed for use on drying beds that allow sufficient drainage. The model has not explicitly been tested for use on beds without these facilities. If it is assumed that S_1=S_0, t_1 =t_0 = 0 and that all the rain that falls on the bed remains on the sludge (b=1), equation 3.1 (c) reduces to equation 3.1 (d).

$$T = t_2 = \frac{30H_0}{aE - R} - \frac{30H_0S_0}{(aE-R)S_2} = \frac{30\ H_0}{aE - R}\ \frac{[S_2 - S_0]}{[S_2]} \qquad \text{3.1 (d)}$$

And equation 3.1 (b) reduces to

$$A_T = \frac{3000\ qs}{aE - R}\ \frac{S_2 - S_0}{S_2} \qquad \text{3.1 (e)}$$

Equation 3.1 (e) shows that A_T is independent of H_0 in these systems, while 3.1 (d) shows a linear correlation between drying time (t_2) and application depth H_0. This is not completely true as the model does not take the insulation effect of dried sludge over wet sludge into account. It is therefore recommended that this model only be applied for thin applications (< 100 mm).

The density of the sludge is assumed to be unity for the purposes of this model and therefore the effective depth of water (h_w) can be calculated for any depth of sludge (H_s) using equation 3.1(f). Here S_w denotes the percentage solids at H_s.

$$h_w = \frac{W.H_s}{100}$$

$$h_w = \frac{(100 - S_W)H_s}{100} \qquad \text{3.1(f)}$$

3.2 DERIVATION OF THE WALSKI MODEL

To illustrate the basis for the equation the derivation thereof is presented below. Figure 3.2 illustrates a sludge in three stages of dewatering. These stages are at the initial bed filling, at the end of drainage and at the point where the sludge is removed.

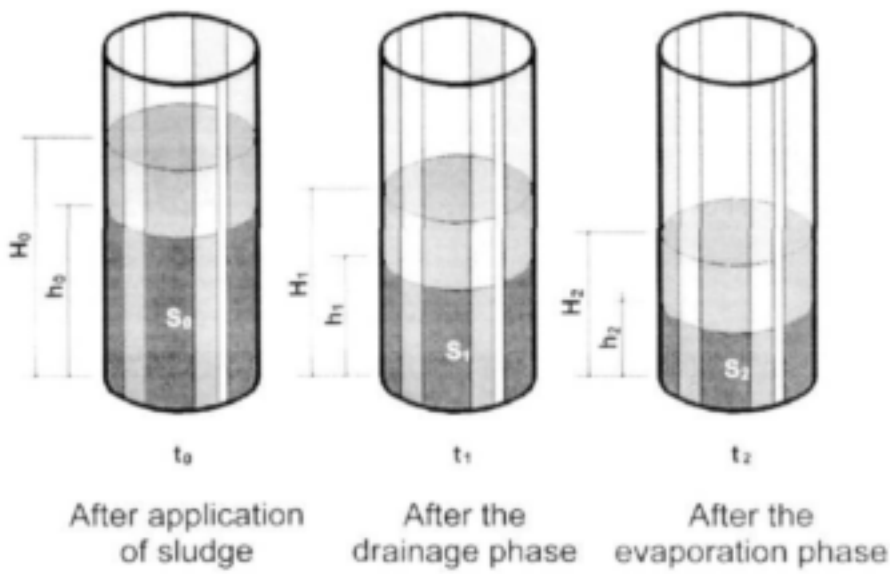


Figure 3.2 : Derivation of the Walski model

From Figure 3.2 and equation 3.1 (d) the following is derived:

Because the sludge solids mass remains constant throughout the dewatering process, the following applies:

$$S_0.H_0 = S_1.H_1 = S_2.H_2 \qquad \text{.......... 3.2(a)}$$

and therefore

$$H_1 = \frac{S_0.H_0}{S_1}$$

$$H_2 = \frac{S_0.H_0}{S_2} \qquad \text{.......... 3.2(b)}$$

Water lost by drainage would then be calculated as h_0 - h_1 and the water lost by evaporation as h_1 - h_2 or

$$h_0 - h_1 = \frac{H_0(S_1 - S_0)}{S_1} \qquad \text{.......... 3.2(c)}$$

$$h_1 - h_2 = S_0.H_0\left(\frac{1}{S_1} - \frac{1}{S_2}\right) \qquad \text{.......... 3.2(d)}$$

The percentage water lost by drainage (% W_d) can be calculated by using equation 3.2 (e)

$$\% W_d = \frac{S_1 - S_0}{S_1} \times \frac{10^4}{100 - S_0} \qquad \text{.......... 3.2(e)}$$

The time required to evaporate water from h_1 to h_2 can be calculated by dividing the amount of water that has to be lost through evaporation by the effective evaporation rate, i.e.:

$$t_2 = \frac{30.H_0.S_0}{aE - bR}\left(\frac{1}{S_1} - \frac{1}{S_2}\right) \qquad \text{.......... 3.2(f)}$$

From the equation it is thus evident that an increase in the numerical values of either b, R, S_2 and S_0H_0 will result in an increase of calculated t_2 values. On the other hand a decrease in a, E and S_1 will also effect an increase of t_2 and A_T. For economic design the parameter values which will effect a decrease in t_2 calculations are of obvious importance.

An example calculation is included below to further demonstrate the sensitivity of S_1, S_2, R and E in application of the Walski model. An experimental program was conducted (Chapter 4) to develop proposed criteria for t_1, S_1, a and b for the purposes of this guide. The experimental work is discussed in Chapter 4.

3.3 EXAMPLE CALCULATION

3.3.1 Demonstration of the effect of solids concentration

The example quoted in the reference literature is included in this section using metric units in order to demonstrate the effect of S_1 and S_2 on specific area A_T / q_s. The values of the variables used in this calculation are listed below.

q_s	=	1000 US gpd (3,78 m^3/d)
H_o	=	12 in (30,48 cm)
t_1	=	2d
S_o	=	10%
S_1	=	20%
S_2	=	50%
E	=	5 in/mo (12,7 cm/mo)
R	=	3 in/mo (7,62 cm/mo)
a	=	0,75
b	=	0,57

A_T and A_T / q_s are consequently calculated by selecting S_1 as 12,5%, 15,0%, 17,5% and 20,0% and varying S_2 between 30%, 40% and 50%. The results are listed in Table 3.3.1 and graphically shown in Figure 3.3.1.

3.3.2 Influence of rainfall and evaporation on area required

The same exercise is repeated to study the influence of rainfall and evaporation on the area required. This is done by selecting E as 10, 15 and 20 cm/month and varying rainfall between 2.5 and 10 cm/month. S_1 and S_2 are taken as 20% and 50% respectively in this case. The results are listed in Table 3.3.2 and are shown graphically in Figure 3.3.2.

Table 3.3.1 : The influence of S_1 and S_2 on specific area

S_1 (%)	S_2 (%)	A_T (m^2)	Specific Area (A_T/q_s)
12.5	30	1045	276
12.5	40	1228	325
12.5	50	1338	354
15.0	30	754	200
15.0	40	937	248
15.0	50	1046	277
17.5	30	546	144
17.5	40	728	193
17.5	50	838	222
20.0	30	390	103
20.0	40	572	151
20.0	50	681	180

Table 3.3.2 : The effect of E and R on specific area

E (cm/mo)	Rainfall (cm/mo)	A_T (m^2)	Specific area (A_T/q_s)
10	2.5	585	155
10	5.0	756	200
10	7.5	1079	286
10	10	1914	506
15	2.5	237	98
15	5.0	430	114
15	7.5	512	136
15	10.0	638	169
20	2.5	275	73
20	5.0	305	81
20	7.5	342	90
20	10.0	391	103

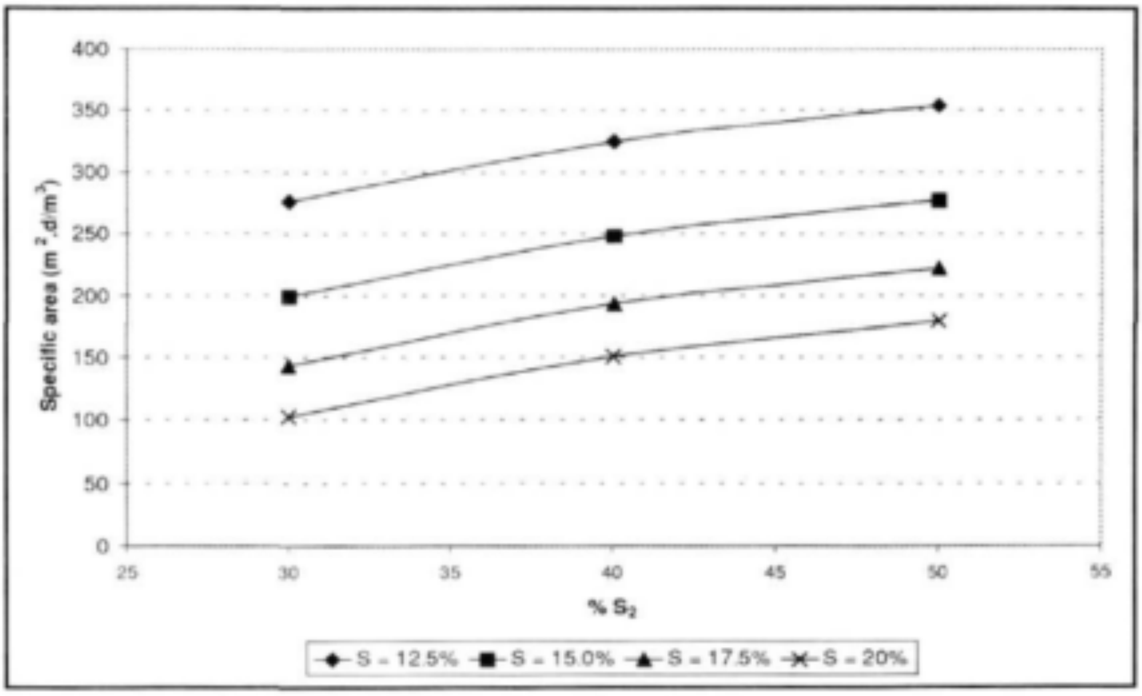


Figure 3.3.1 : The influence of S1 and S2 on a specific area

3.3.3 Interpretation

The equation indicates that the area required is relatively insensitive to the depth of application H_0. The only effect of depth (if H_0 is multiplied through in the denominator) is when t_1/H_0 is not constant. As long as t_1 is proportional to H_0, it is of no significance. As t_1 is not proportional to H_0, the result implies that some savings in cost can be realised by increasing H_0.

The sensitivity of specific area (A_T/q_s) on varied solids concentration is shown in Figure 3.3.1. The figure shows the extreme sensitivity of area on S_1. This means that sludges that drain easily will use significantly less area, indicating the need for accuracy in determining S_1 in laboratory analysis.

The sensitivity to evaporation factors is shown in Figure 3.3.2. This figure indicates that the required area increases to infinity as effective evaporation approaches zero. In such instances drying beds would obviously require covers.

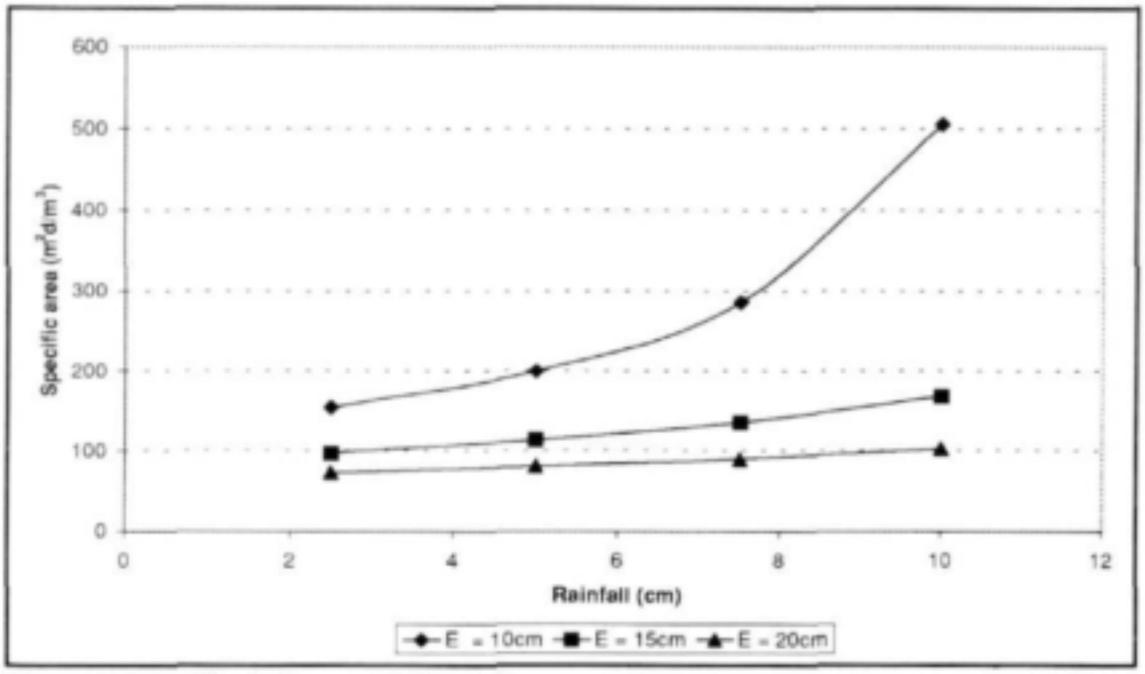


Figure 3.3.2 : The influence of E and R on a specific area

The formula does not explicitly distinguish between different sludge types. The differences in dewatering characteristics are studied in Chapter 4. Since the differences primarily affect the draining phase of sludge dewatering, the characteristics of the sludge will implicitly be accounted for in the t_1 and S_1 terms. Sludges that do not dewater well will have larger values for t_1 at which time S_1 will still be relatively low. This will result in a larger surface area being required than for easily dewatered sludges.

CHAPTER 4

LABORATORY AND FULL-SCALE TESTING

4.1 INTRODUCTION

The objectives of these tests were aimed at verification or assessment of the prime parameters required for application of the Walski Design model (Chapter 3). Laboratory scale columns were used to determine S_1 and t_1 for both anaerobic digested (AD) and activated (AS) sludges. Initial concentrations (S_0) were varied by dilution or concentration of the original sludge samples. The laboratory drainage columns used in this study are shown in Figure 4.1.

The complete study is too comprehensive to include in this guide, and is compiled into a set of working papers which is held in the library of GFJ (Pty) Ltd.

Artificial rainfall (AR) was added during various stages of drainage to estimate the b-factor. The water absorption capacity (WAC) of air-dried AD and AS sludges was also compared to determine rainfall absorption under simulated conditions of extreme rainfall and after completion of the evaporation period (t_2). Evaporation dishes were used to determine the evaporation from sludge relative to clean water (a-factor).

Several reports from the literature were studied to complement the results derived from this study, particularly on the drainage parameters S_0, S_1 and t_1.

Two full-scale test beds (TB1 and TB2) were also used in parallel to compare dewatering parameters for AD and AS sludges during a full drying cycle during a dry period. A third test bed (TB3) charged with AD sludge was also monitored during a period of high monthly rainfall and compared with TB1.

The test results are briefly summarised, discussed and interpreted in this chapter. It should be appreciated that these results are highly empirical and within the limited scope for statistical and fundamental studies allowed for in the compilation of this guide. It is envisaged, however, that these results could provide the designer with reasonable guidance in using the Walski model for the design of sewage sludge drying beds.

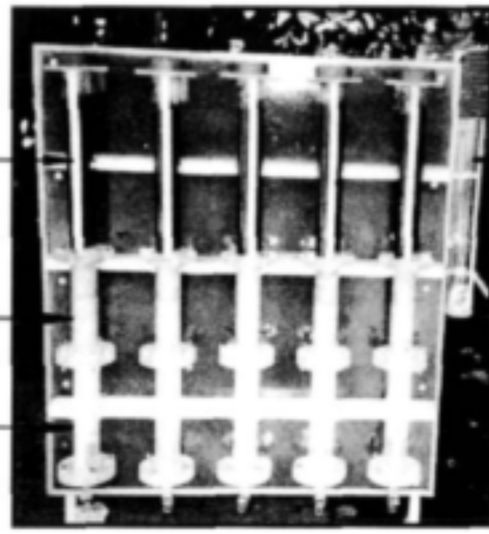


Figure 4.1 : Six 52 mm diameter columns used to study the variables that influence sludge dewatering

4.2 DESIGNATION OF SLUDGES USED

The sludges used in laboratory and full-scale tests were sourced from various plants and had varying characteristics. For the purposes of this chapter the sludges will be referred to as follows:

AD-1 : Anaerobic digested sludge from (Source I) (S_0 = 2,93%), comprising of about 40% waste activated and 60% primary sludges which were combined in digesters. This sludge was used for laboratory drainage tests in parallel with TB1.

AD-2 : Anaerobic digested sludge (S_0 = 3,60%), used to prepare dilutions for laboratory drainage tests, also TB3 (Source I).

AS-1 : Activated sludge DAF thickened (S_0 = 2,57%) and used on TB2. The sludge age was about 11 days (Source I).

AS-2 : Waste activated sludge ex Source II (S_0 = 0,4%); thickened to S_0 = 1,0% for drainage tests. Sludge age > 30 days (well-stabilized).

AS-3 : DAF thickened ex Source III (S_0 = 4,0%); dilutions prepared for drainage tests; Relatively long sludge age (>20 days).

DS-1 : Air-dried digested sludge ex Source I for water absorption tests capacity (WAC) (S_2 > 80%).

DS-2 : Air-dried activated sludge ex Source I for WAC tests (S_2 > 80 %).

DS-3 : Air-dried anaerobic digested sludge ex Source II for WAC tests (S_2 > 80%).

DS-4 : Air-dried activated sludge ex Source II for WAC tests.

4.3 GRAVITY DRAINAGE TESTS

4.3.1 Methodology

Drainage tests were conducted using various sludges. The sludges were loaded in the test columns and the variable depth of sludge above the filter media (H_s) and accumulated drainage (H_d) were recorded with time. The initial concentration of solids (S_0) was determined in the laboratory and the solids concentration during or after drainage (S_0 - S_1) was estimated as follows:

(H_0 denotes the depth of sludge (cm) loaded at t_0). Equation 4.3.1(a) is derived based on the drainage collected from a sample. This estimate was verified using the initial and final depths of the sludge (i.e. H_0 & H_1)

$$\frac{H_0\ S_0}{H_0 - H_d} = \frac{H_0\ S_0}{H_1} \qquad \text{. . . . . 4.3.1(a)}$$

In some cases S_1 was gravimetrically determined in the laboratory (denoted by S^*). S_1 is based on the assumption that the density of the drained sludge is equal to unity. However, S_1 , based on H_d, would be influenced by the leakage water used during the preparation of the columns which remains in the column when it is charged with fresh sludge. A correction factor for leakage was estimated from a blank column run in parallel.

4.3.2 Interpretation of drainage results

The results from the drainage experiments are presented in Figures 4.3.2 (a) to 4.3.2 (c). Figure 4.3.2 (a) depicts the depth of sludge bed (H_s) and drainage (H_d) with time for AD-1 sludge. Averages of 5 parallel tests are recorded. A close agreement between ΔH_s and ΔH_d is demonstrated for this particular sludge.

Drainage curves for AD-2 dilutions with tap water are shown in Figure 4.3.2 (b) with estimates of t_1 and S_1 values. The t_1 and S_1 values increase S_0 with concentrations.

Drainage curves for AS-3 dilutions using DAF underflow for dilution are shown in Figure 4.3.2 (c) with estimates of t_1 and S_1. The t_1 and S_1 values also increased with S_0 but were significantly lower than for AD-2 sludges.

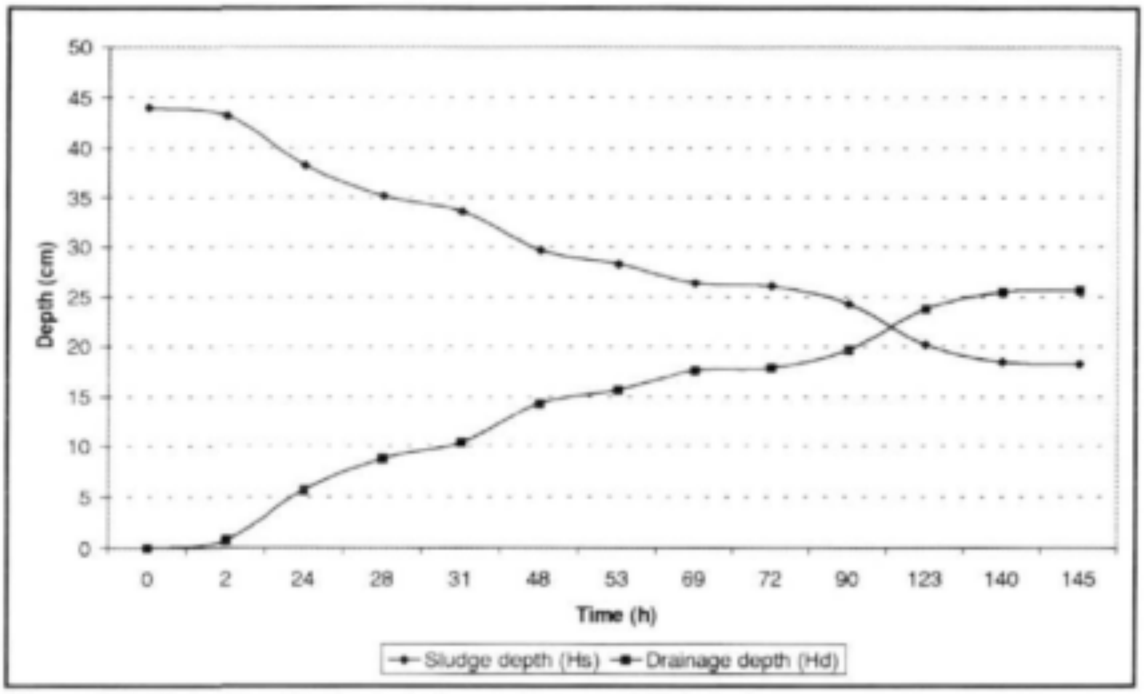


Figure 4.3.2(a) : Results from drainage tests on AD-1 sludge

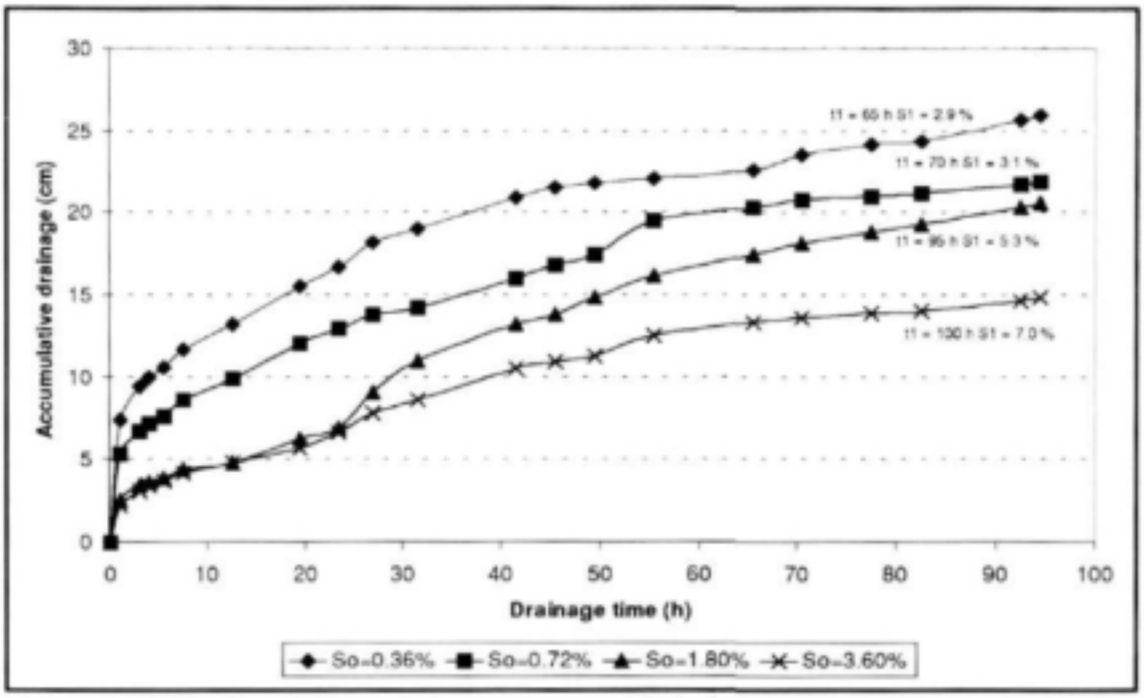


Figure 4.3.2(b) : Results from drainage tests on AD-2 sludge

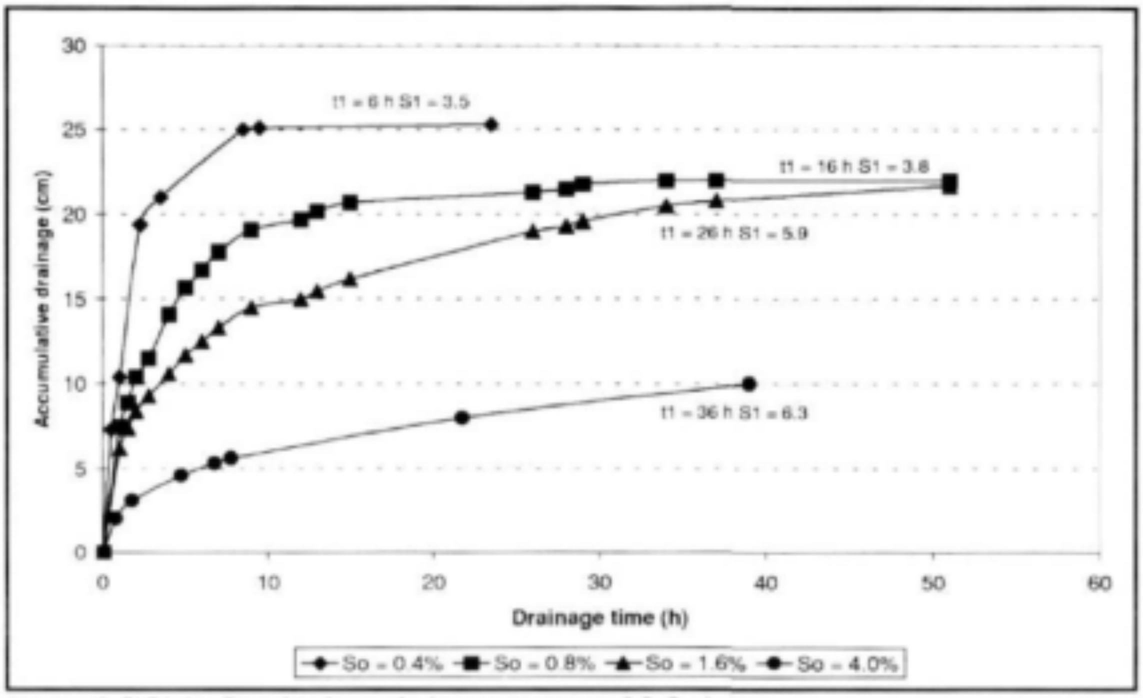


Figure 4.3.2(c) : Results from drainage tests on AS-3 sludge

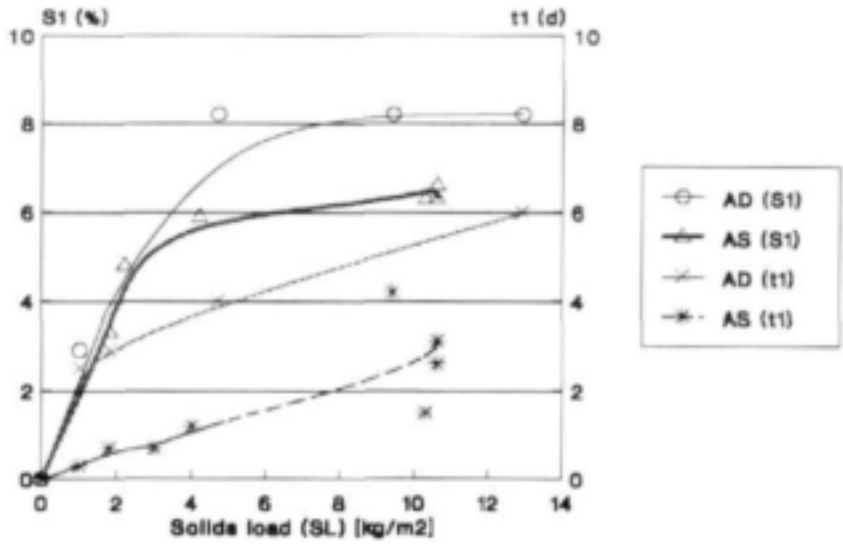


Figure 4.3.2(d) : A comparison between AD and AS sludges indicating the effect of solids load on S_1 and t_1

From the drainage curves rough estimates of t_1 and S_1 were made. As expected t_1 is difficult to define accurately and estimates are made from the declining gradients of the curves.

In the case of dilute sludges the t_1 values are relatively short and calculated S_1 values are highly sensitive to (H_0-H_d). A summary of estimated t_1 and S_1 values is given in Table 4.3.2. From these results an attempt was made to graphically present t_1 and S_1 values against Solids Load for AS and AD sludges. (See Figure 4.3.2 (d). From this figure it appears evident that drainage times t_1 for AS are significantly less than for AD sludges. However the resultant (S_1) is also comparatively less for AS, i.e. a "wetter" sludge remains to be dewatered during the evaporation period t_1 to t_2. This could probably be ascribed to a larger fraction of bound water for activated sludges (AS).

4.3.3 Test bed drainage experiments

Two adjacent sludge drying beds from Source1 (TB1 and TB2) with a surface area 225 m^2 each were filled with AD-1 and AS-1 sludges respectively. Routine daily measurements of sludge levels were made during a drainage period of about 8 days. Because of variations in filter media depth a number of fixed monitoring points were selected to determine average sludge depths. The S_1 and t_1 values were estimated from variable sludge levels (H_0 to H_1) (Figure 4.3.3 (a)).

These tests were done to verify the bench-scale test results for AD-1. Fair agreement was found as is shown in Table 4.3.2.

Table 4.3.2: Summary of data from drainage experiments

Sludge Type	S_o (%)	H_o (mm)	H_1 (mm)	H_d (mm)	t_1 (days)	S_1 (%)	SL (kg/m^2)
AD-1	2.93	44	18.3	25.6	6.0	8.23 7.04*	12.9
AD-2	0.36	26	-	22.8	2.6	2.9	0.9
AD-2	0.72	26	-	20.4	2.9	3.3	1.9
AD-2	1.8	26	-	20.4	4.0	8.3	4.7
AD-2	3.6	26	-	14.4	4.2	8.1	9.4
AS-2	0.34	30.1	-	28.6	0.3	6.8	(1.0)
AS-2	1.0	30.1	-	25.2	0.7	6.1	(3.0)
AS-3	4.0	26	-	9.5	1.5	6.3 6.7*	10.4
AS-3	1.6	26	-	19.0	1.1	5.9	4.2
AS-3	0.8	26	-	20.5	0.7	3.8	2.1
AS-3	0.4	26	-	23.0	0.25	3.5	1.0
AS-3	4.0	26.4	20.2	9.5	2.6	6.2 5.2*	10.6
AS-3	2.9	36.4	20.0	16.2	3.2	6.5 5.3*	10.6
AD-1	2.93	24.3	8.5	-	6.8	7.65 8.37*	TB1 7.1
AS-1	2.57	22.4	10.6	-	7	6.20 5.43*	TB2 5.8

* Denotes laboratory results

The increase in solids concentration (S_s) with time is shown in Figure 4.3.3(b) which demonstrates dewatering for the digested sludge compared to that of the DAF activated sludge.

Samples for laboratory solids determination were taken during the full dewatering cycle. After 21 days the AD-1 sludge was at 40% solids compared to ≈ 20% for AS-1. The AD-1 sludge had dried to approximately 90% solids at the time as the AS-1 sludge only had reached 40% moisture content (Figure 4.3.3 (b)). These results indicate poorer dewatering for the DAF AS-1 than for AD-1 sludge.

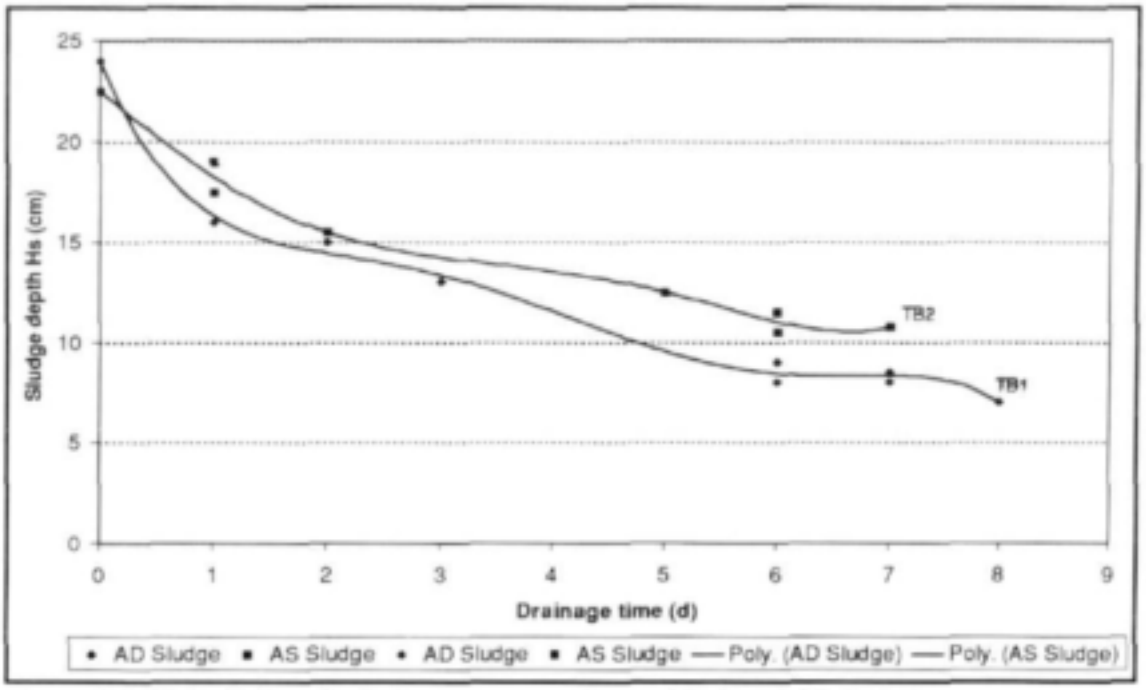


Figure 4.3.3(a) : Full-scale drainage test results on AD-1 and AS-1 sludges

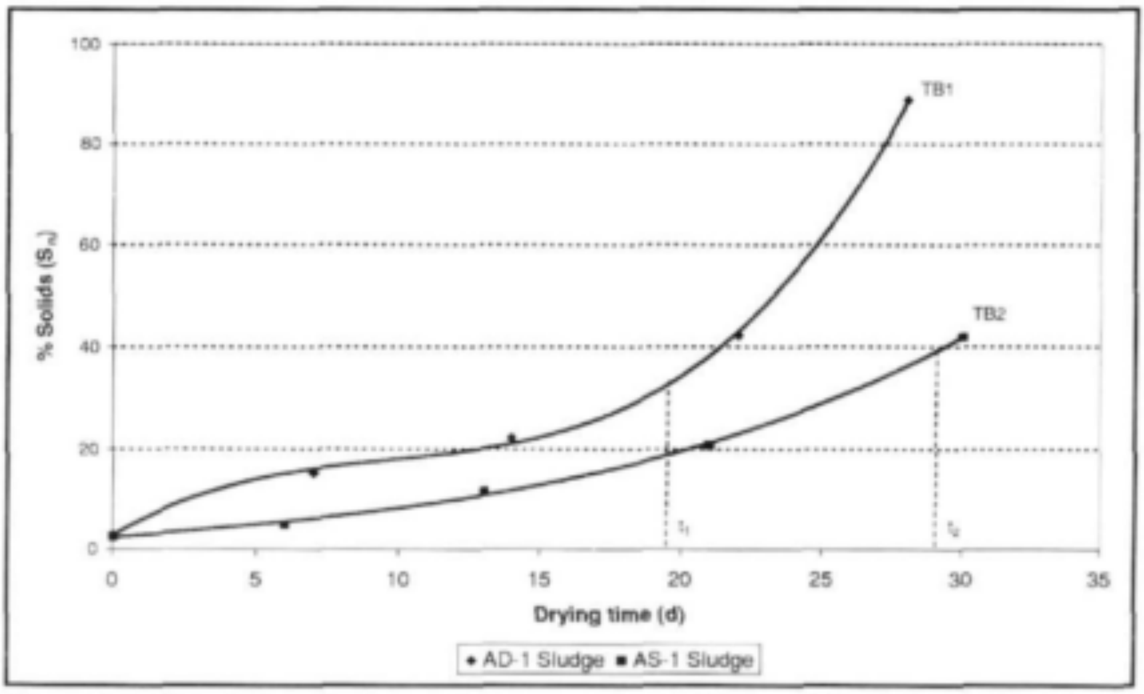


Figure 4.3.3(b) : Full-scale dewatering test results of AD-1 and AS-1 sludges

The Walski model was applied to these results under conditions of minimal rainfall (b=0) and using a=0,75 and E=15,3 cm. The calculated T values (the time taken to reach a haulable sludge of S_2 = 40%), were in close agreement (within 1 day) with the experimentally monitored dewatering time.

It should be noted that the AS-1 in TB2 had a relatively short sludge age of 11 days which partly explains the inferior dewatering behaviour. Obnoxious odours and flybreeding were observed at this bed. The solids loads for TB1 and TB2 were respectively 7,12 and 5,76 kg/m^2. It appears that activated sludges should only be considered for dewatering on drying beds if they are well stabilized and if they are applied at lower SL than digested sludges.

4.3.4 Further interpretation of drainage results

For application of the Walski model an estimation of t_1 and S_1 is essential. As with other models it is unlikely that these parameters will be known for different sludge types during the design phase. The drainage data obtained from these studies as well as those derived from the literature was subjected to regression analyses and exponential equations were fitted to them. The results for three types of sludges lead to the following empirical relationships where SL denotes the sludge loading. The correlations are also presented graphically in Figure 4.3.4 (a).

Well stabilised activated sludge (sludge age 20-25 days) (Sludge A):

$$\frac{S_1}{S_0} = 22{,}8\,SL^{-0{,}92} \qquad \text{.......... 4.3.4(a)}$$

Poorly to medium stabilised activated sludge (Sludge B)

$$\frac{S_1}{S_0} = 9.17\,SL^{-0.68} \qquad \text{.......... 4.3.4(b)}$$

Anaerobically digested (mixed primary and waste activated sludge) (Sludge C):

$$\frac{S_1}{S_0} = 9{,}0\,SL^{-0{,}54} \qquad \text{.......... 4.3.4(c)}$$

The equations presented in this section are derived from limited data and require further research and refinement. These empirically derived equations are recommended for estimating S_1 which is needed in the Walski model. Ideally a laboratory determination for a particular sludge would be more accurate but this is of course only possible for an existing sewage works.

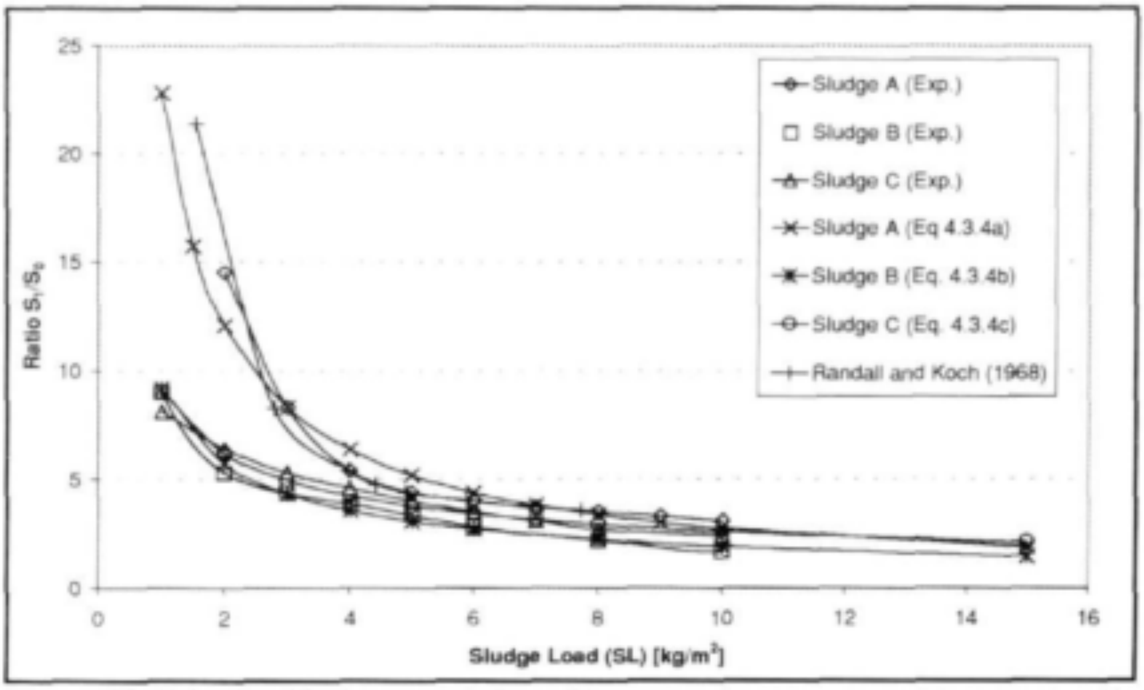


Figure 4.3.4(a) : Graphical representation of the regression curves used to determine S_1

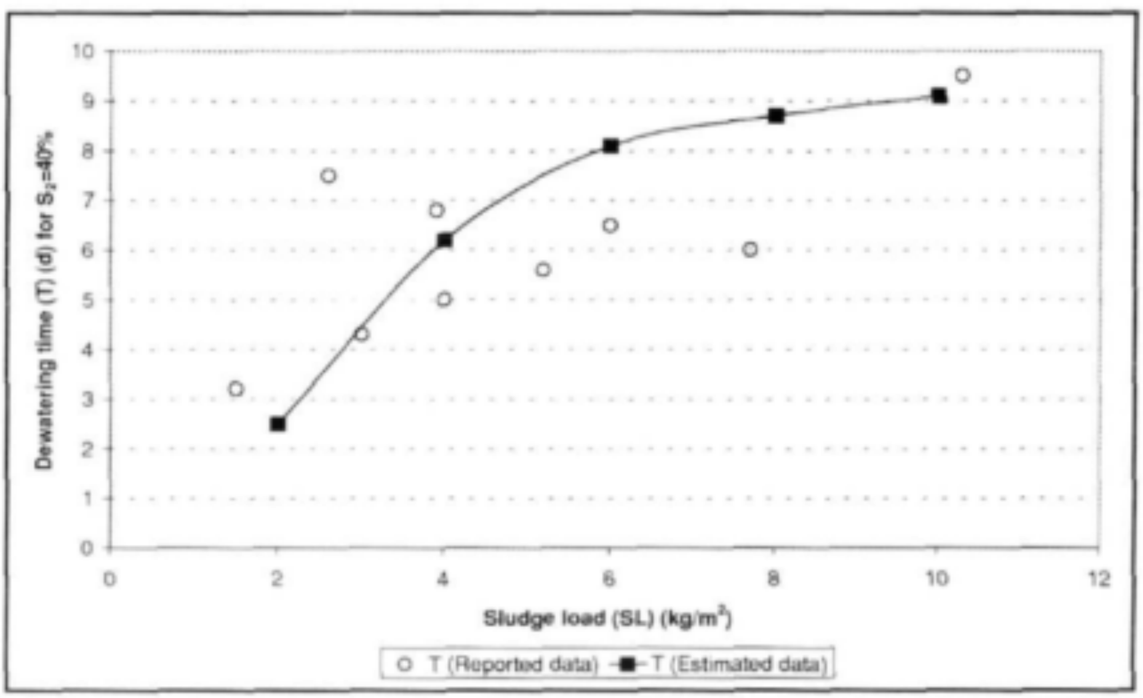


Figure 4.3.4(b) : Comparison of Walski's estimated values with Randall and Koch's (1968) experimental data

From Fig. 4.3.4 (a) it can be seen that S_t/S_0 decreases with increased SL. A similar curve could be derived from work done by Randall and Koch (1968) on aerobically digested sludges. This curve is also presented in Fig 4.3.4 (a) and shows a good correlation with other data sets. This implies that increasing sludge loads will reduce the percentage of water that drains from the sludge leaving a larger fraction to be evaporated.

A comparison was made between Randall and Koch (1968) experimental data and the Walski model. This comparison is shown in Figure 4.3.4 (b). The results are obviously dependent on the accuracy of the input data but for practical purposes the Walski model appears to be valid although slightly conservative.

As mentioned previously the importance of the drainage phase should not be underestimated. *The percentage of water lost by drainage (W_d) is shown in Figure 4.3.4 (c).*

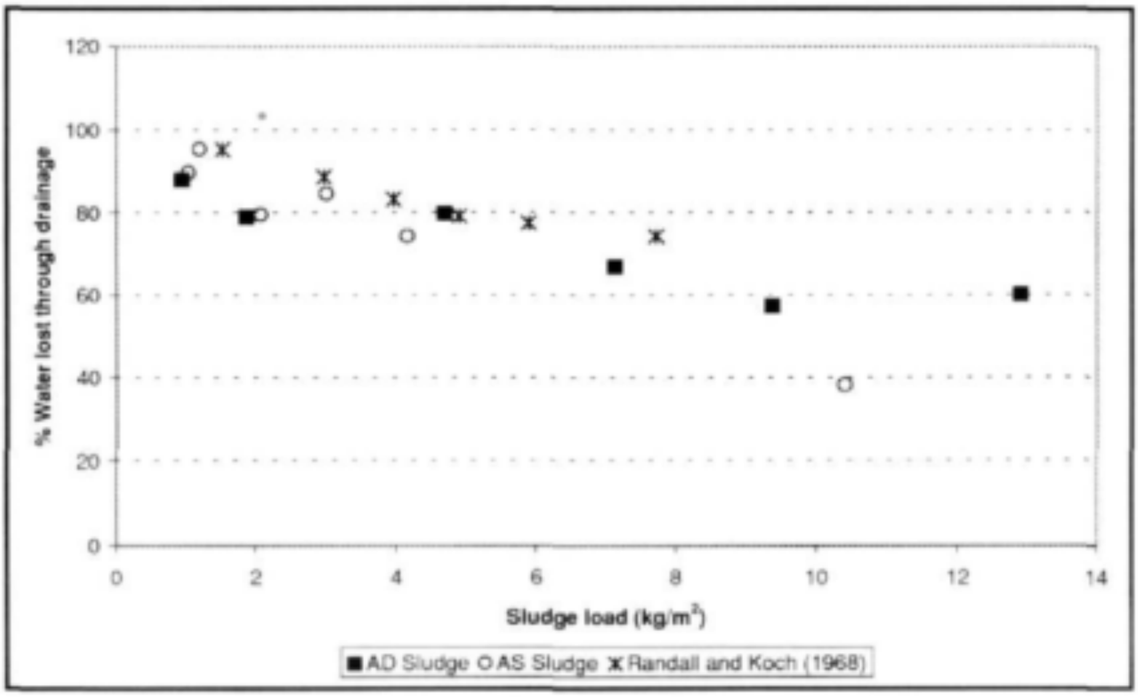


Figure 4.3.4(c) : Percentage water lost by drainage (%W_d)

For practical purposes % W_d follows the same declining rate with increased SL for both activated and anaerobically digested sludges.

What is also significant is the amount of water lost in the drainage phase. The results confirm that the drainage mechanism accounts for more than 75% of the water removed from the sludge over a relatively short drainage period.

Beds that are therefore not provided with adequate drainage facilities are left to evaporate this water which will lead to vastly extended total dewatering times. Data from the Randall and Koch (1968) report on aerobically digested sludges is also included.

Using the data published in literature and also the data generated during the compilation of this guide, tentative guidelines are given for estimating t_1 in Table 4.3.4.

Table 4.3.4: Guidelines for S_1 and t_1 for use in the Walski model

	Activated sludge (Well stabilised) eq. 4.3.4(a)		Activated sludge (Poorly stabilised) eq. 4.3.4 (b)		Anaerobically digested sludge eq. 4.3.4 (c)	
SL [kg/m^2]	S_1/S_0	t_1 [days]	S_1/S_0	t_1 [days]	S_1/S_0	t_1 [days]
1,5	15,7	< 1	7,0	< 1	7,2	3
3,0	8,3	< 1	4,3	< 1,5	5,0	4
4,5	5,7	< 1	3,3	< 1,5	4,0	4,5
6,0	4,4	< 1	2,7	~ 1,5	3,4	4,8
7,5	3,6	~ 1	2,3	< 2,0	3,0	5,0
9,0	3,0	< 1,5	2,1	< 2,0	2,7	6,0

The guidelines presented above do not apply to DAF thickened sludges of poor stability. Furthermore it is important to keep in mind that the determination of S_2 with the Walski model is dependent on the accuracy of S_1 and therefore S_1 should be determined with laboratory tests if at all possible. To err on the side of safety, S_1 could be taken on the low side as this will increase t_2 values and thereby introduce a factor of safety.

4.4 EVAPORATION TESTS (a-FACTOR)

Several tests were conducted using different sludges to verify the a-factor for effective evaporation as used in the Walski Model (a=0,75). This was done by filling two identical evaporation pans (≈ 30 cm diameter) with about 5 ℓ of sludge and tap water respectively. These were exposed to the atmosphere and weighed on a daily basis.

Solids concentration (S_n) during evaporation was calculated from the original solids concentration (S_0); original sludge mass (M_o), and residual sludge mass M_n.

$$S_n = \frac{S_0 . M_o}{M_n} \qquad \ldots\ldots\ldots\ldots \; 4.4(a)$$

The a-factor was calculated from the relative mass losses for sludge and water. The results obtained are briefly summarised below.

AD-1 sludge (S_0 = 2,93%) (SL = 2,2 kg/m^2)
The a-factor appeared close to unity up to about 8% S_n content. An "average" value of 0,79 was estimated for a S_n range of 8% to 46%.

AD-3 sludge (S_0 = 3,58%) (SL = 1,15 kg/m^2)
The a-factor up to about 12% S_n was on average 1,19 and for 12% to 36% on average 0,87. An a-factor that is larger than unity is also reported by a number of other authors (Adrian, 1978).

AS sludge (S_0 = 1,5%) (SL = 0,6 kg/m^2)
The a-factor up to about 13% S_n was close to unity. From S_n equal to 13 to 40% the average a-value was estimated at 0,72.

From these results the proposed value by Walski of a = 0,75 appears acceptable. The results further indicate that the a-factor only becomes relevant at higher solids content of 8 to 13% which is in fair agreement with the literature. It should be noted that these estimates of the a-factor are based on relatively low experimental SL-values (0,6 - 2,2 kg/m^2). A gradual decrease in the a-factor is anticipated for increased SL, particularly for AS of poor stability.

4.5 RAINFALL ABSORPTION (b-FACTOR)

4.5.1 General

The effective evaporation term (aE-bR) for application of the Walski model assumes the b-factor to be constant. Based on the original work of Swanwick the mean value of b for 15 separate observations was estimated at 0,57. This value relates to anaerobically digested sludges at 30 cm loading depth indicating a relatively high solids load (SL = 15 kg/m^2 at an assumed S_0 = 5%). No indication is given of the possibility that the b-factor could be reduced by lowering SL (e.g. SL = 1,5 kg/m^2 assuming S_0 = 0,5%) such as for waste activated sludges. Furthermore the range for R is unspecified. The assumption that b remains constant for a variable R appears to be oversimplified.

A number of tests were conducted using the laboratory drainage columns to assess the b-factor. Rainfall was simulated after completion of gravity drainage (i.e. at t_1) as this condition was assumed to be representative of the worst case scenario. Rainfall prior to t_1 and prior to the formation of the blinding layer is thought to act as a simple dilution of the sludge in which case the bulk of the rainwater would simply drain away.

Should rainfall occur sometime after t_1, the sludge would most probably have started to crack. The rainfall would simply drain through the cracks and would leave a smaller percentage to be absorbed by the sludge cake. The cake would also have started to lose its water retaining capacity as will be shown later.

Because of the importance assigned to the b-factor, special attention was devoted to this aspect. The main findings are briefly summarised and discussed in the following paragraphs.

Adrian (1978) conducted experiments using 500 mℓ of well mixed sludges and fitted glass funnels. The sludges were allowed to dewater until they reached the desired moisture content within the "falling rate" drying phase, i.e. 21% to 36%.

Daily rainfall varying between 0,25 and 10 cm was added and allowed to drain. By regression analyses the following equation was derived to describe what influence rain had on drying sludges (equation 4.5.1(a)):

$$M = 4{,}68\,M_0^{0{,}766} R^{0{,}056} \qquad \ldots\ldots\ldots\ 4.5.1\ (a)$$

where M_0 = moisture-solids ratio before the rain [%]
M = moisture-solids ratio after the rain [%]
R = rainfall [cm/d].

Results from this equation were in good agreement with results generated through their experimental work as can be seen from Table 4.5.1(a).

Table 4.5.1(a): Comparison of measured and calculated moisture contents (Adrian, 1978)

R (cm/d)	M_0 (%)	M (Experimental)	M (Calculated)
0,25	272,1	314,2	317,6
0,51	229,3	289,2	289,6
1,02	266,3	334,9	337,6
1,27	286,2	360,1	361,2
2,54	275,7	370,5	365,0
5,08	277,6	384,6	381,4
10,16	319,2	426,7	433,8

These results were studied in an attempt to determine what the influence of a varying R-value would be on the b-factor.

As Adrian (1978) had not given the diameter of the glass funnel used in his work it was not possible to determine the exact solids load (SL) used. It was therefore necessary to work with various estimates of this value. By substituting these estimates into equation 4.5.1 (b) a number of b-factors could be generated. These are given in Table 4.5.1(b).

$$\frac{b}{SL} = \frac{M - M_0}{1000R} \qquad \ldots\ldots\ldots\ 4.5.1\ (b)$$

The estimates presented above are valuable to demonstrate the relative effects of rainfall and solids loading on the fraction of rain absorbed into the drying sludge cake. They are not recommended as criteria for this guide.

Table 4.5.1(b): b-Factors generated from Adrian (1978)

R (cm/d)	b/SL (from eq. 4.5.1(b))	b (at SL = 2 kg/m²)	b (at SL = 4 kg/m²)	b (at SL = 6 kg/m²)	Limiting SL (b = 1)
0,25	0,18	0,36	0,72	1,08	5,55
0,51	0,12	0,24	0,48	0,72	8,33
1,02	0,07	0,14	0,28	0,42	14,3
1,27	0,06	0,12	0,24	0,36	16,7
2,54	0,035	0,07	0,14	0,21	28,6
5,08	0,02	0,04	0,08	0,12	50,0
10,16	0,011	0,022	0,04	0,07	90,1

The following conclusions could be drawn from the above table.

(i) At constant SL the b-factor decreases with increased R. It should be noted that b represents the *fraction* of rainfall absorbed and that increased R implicitly increases the *mass* of rain absorbed.

(ii) At constant R, the b-factor increases with SL. For each R there appears to be a limiting SL-value beyond which all rain is absorbed. The value obviously increases with R.

(iii) The rainfall (R) is expressed in cm/d. For the Walski model the rainfall for a typical "wet month" is required. Interpretation or utilisation of the above R and b-values in the Walski model is rather complex. Maximum annual averages of rainfall in high rainfall areas in South Africa rarely exceed 2000 mm/a. On a daily average this extreme rainfall hardly ever averages 5 mm/d. The question arises how rainfall data must be interpreted and what b-factors must be assigned for use in the Walski model. Evidently appreciable scope for further research remains.

A further discussion follows in paragraph 6.3.3.

4.5.2 Rainfall absorption by anaerobically digested sludge (experimental)

The results of the initial absorption tests performed on anaerobically digested sludge in the course of the compilation of this guide are presented in Table 4.5.2(a). The results indicate b-values of 0,13 to 0,34 for R ranging from 13 to 27 mm per month distributed over a period of 2 to 3 weeks and SL of 12,9 kg/m².

Test columns A to E were allowed to drain completely after the rainfall experiments. Simulated rainfall ranging between 1 to 5 cm were applied and total drainage collected after 8 days. The sludge cakes were then removed and solids concentration determined. The results are shown in Table 4.5.2 (b).

Results indicate estimated b-factors ranging from 0,2 to 0,47 for incidental rain ranging from 1 to 5 mm. The percentage solids in the sludge cakes significantly decreased with increased rainfall.

Table 4.5.2 (a) : Rainfall absorption by anaerobic digested sludge (AD-1 Sludge type)

Column	A		B		C		D		E	
Time (d)	R	D	R	D	R	D	R	D	R	D
0	0	0	212	0	159	0	106	0	53	0
6	0	(75)	0	232	53	195	53	112	53	75
12	212	(25)	212	38	0	53	53	57	53	48
16	0	185	0	195	0	22	0	60	53	45
18	53	4	106	8	159	10	212	9	0	47
23	21	40	43	76	64	142	85	170	106	12
25	0	5	0	8	0	7	0	7	0	9
32	0	15	0	29	0	34	0	68	0	74
Total Correction D*	286	349 249	573	586 486	435	463 363	509	483 383	318	310 210
$b = \frac{R - D^*}{R}$	0,13		0,15		0,1		0,26		0,34	
R (cm)	13,5		27,0		20,5		24,0		15,0	
Time range(d)	13		23		23		23		23	

Where: R = Rainfall (cm)
S_0 = 2,93% SL = 12,93 kg/m²
D = Drainage collected (cm) H_0 = 44 cm
Note: 1 cm = 21,23 mℓ in the test columns used

Table 4.5.2 (b) : Continued rainfall experiments

Column	A	B	C	D	E
Rain (cm)	1,0	2,0	3,0	4,0	5,0
b-factor	0,29	0,32	0,47	0,20	0,30
% Solids	22,5	19,7	18,8	16,5	15,8

4.5.3 Rainfall absorption by activated sludge

Drained activated sludges with solids loads ranging from 1 to 10 kg/m^2 were subjected to 10 cm of rain and drainage was collected after 4 days, at which time further drainage appeared minimal. The b-factor was estimated after 4 days. The blinding layer in the media interface was then disrupted which resulted in further rapid drainage (within 2 - 3 hours). The additional drainage induced in this way increased the total amount of drainage to levels that compared well with the amount of "rainfall" applied. The results are shown in Table 4.5.3.

Table 4.5.3 : Rainfall absorption by activated sludge

SL kg/m^2	Rain added cm	Drainage after 4 days (cm)	Apparent b-factor	Additional drainage after disruption
1,04	10	9,4	0,06	-
2,08	10	4,2	0,58	7,4
4,16	10	3,0	0,70	7,5
10,40	10	3,5	0,65	7,1

These results point strongly to the blinding layer causing resistance to drainage of rain, particularly at high SL (2 to 10 kg/m^2). Indications are that the b-factor relates to the resistance to filtration caused by the blinding layer and not by the physical absorption of rain on solids.

Further tests were also conducted with drained anaerobic digested sludge with SL ranging from 0,9 to 9,2 kg/m^2 and applying 10 cm of artificial rain. Drainage collected after two days (with disruption of interface) confirmed virtually complete drainage of rain ($b < 0,1$). After 4 days the columns were re-charged with 10 cm of rain. A further 6 days were allowed for drainage (this time without disruption of the interface) and for all practical purposes the charged rain was quantitively drained in all experimental columns.

During a period of high rainfall (17,4 cm/month) a further test bed (TB-3) was monitored over the full dewatering cycle of an AD-1 sludge. An a-factor of 0,75 was assumed and the b-factor estimated from the experimentally determined Walski parameters (H_0, S_0, S_1, S_2 and T). This resulted in a b-value of 0,28.

These results indicate the following:

(a) For AD sludges (SL~10 kg/m^2) the b-factor is substantially lower than the value of 0,57 as quoted in the literature. A value of b=0,20 is suggested for high rainfall areas (R>10 cm/m). For low rainfall (R<10 cm/m) a value of b = 0,3 is recommended.

(b) For activated sludges b = 0,4 is recommended.

4.5.4 Water absorption capacity of dried sludges (WAC)

Air dried sludges were tested for WAC under conditions simulating extreme rainfall. An empirical method was used whereby ±100 g sludge was soaked with 1 ℓ of water for 2 to 5 hours and the mass of water absorbed was determined. The objective was to roughly estimate b during conditions of excessive rain when sludges are already haulable (i.e. after t_2, S_2).

Results are listed in Table 4.5.4.

Results confirm higher WAC for waste activated than for anaerobic digested sludges. For well-stabilised waste activated (DS-4) the values were lower than for the DAF-thickened DS-2 sludges. The WAC appears to have value as a crude estimation of the b-factor. At the very least it could be used to compare the dewatering ability of various sludges relative to each other. For example, if 100 g of dried sludge absorbs about 200 mℓ of water from supernatant, the maximum b-value cannot be higher than 2, i.e. 200 mℓ/100g.

For a given SL and R assuming WAC of 2,0 the following example applies:

SL	=	15 kg/m^2
R	=	10 cm
WAC	=	2,0
R/m^2	=	0,1 x 1000 = 100 kg
R absorbed	=	15 x 2 = 30 kg
b	=	30/100 = 0,3

Table 4.5.4 : Measured water absorption capacities

Sludge Type Refer par. 4.2	Water Absorption Capacity (WAC)	Saturation Time (h)
DS-1	1.67 1.58 1.50 1.64	3 3 2 5
DS-2	1.86 1.99 2.10	2 3 5
DS-3	1.22	3
DS-4	1.40	3

This value is considered conservative because of crack formation in practise. These results indicate that b-values during the intermediate **evaporation stages** approaching t_2 will not be excessive especially when well-defined cracks have been formed.

CHAPTER 5

THE CURRENT SITUATION IN SOUTH AFRICA

5.1 GENERAL

The prime purpose of this guide is to address the problems that designers and operators currently face in South Africa regarding sludge drying beds. In order to determine what these problems are and also to try and find some solutions to these problems, questionnaires were sent out to 536 local authorities, several plants were visited and interviews were held with designers and operators.

5.2 QUESTIONNAIRES

Of the 536 questionnaires distributed to local authorities 121 were returned. Of these 30 authorities used sludge beds, and these yielded some information that was scrutinised for points of relevance to design. In order to simplify analysis and comparison the returned questionnaires were classified under activated sludges (AS), anaerobic digester (AD) and combined plants (AD). It was evident that some information, especially regarding volumes and concentration of sludges, were based on rather crude estimates. The data contained in some of the questionnaires are summarised in Tables 5.2(a), 5.2(b) and 5.2(c), where the variables have the following meaning.

Q_c	=	Current sewage flow (m^3/d)
Q_d	=	Design sewage flow (m^3/d)
q_s	=	Approximate volume of wasted sludge (m^3/d)
$\%S_0$	=	Solids concentration at application (%)
A	=	Area per bed (m^2)
A_T	=	Total area provided (m^2)
H_0	=	Depth of sludge application (m)
T_d	=	Dry season drying times (d)
T_w	=	Wet season drying times (d)
A_{Td}	=	Bed area required in dry times (m^2)
A_{Tw}	=	Bed area required in wet months (m^2)

Processing of field data in this section was essentially aimed at the following objectives:

(i) to estimate sludge production rates for different plants,
(ii) to estimate and compare sludge bed loading rates and drying cycles, and
(iii) testing of Walski Design model.

The Walski Model was tested by determining the drying time through use of equation 5.2 for determining the total bed area required.

$$A_T = \frac{q_s}{H_0} T \qquad \text{.............} (5.2)$$

The calculated A_T value was compared with the total installed bed area for specific plants (A_T). This comparison should give some perspective of over- and under-design or validity of the reported values. The T-value can then be compared with reported drying times and used to calculate A_T for comparison with the installed bed areas. The results are included in Tables 5.2 (a), 5.2(b) and 5.2(c). A graph showing the results is presented in Figure 5.2. The comparison between Walski and the reported data was made for wet and dry periods. If a perfect correlation existed, all the points would have fallen on the diagonal line. This is, however, not the case and no correlation exists.

In general the evaluation of the questionnaires received proved to be a difficult exercise. No strong correlations could be found. Graphs showing typical spreads in data received are presented in Figure 5.2. This is ascribed mainly to inaccurate reporting by some respondents. Where the reported values were obviously incorrect, the respondents were contacted and the issues were discussed. In more than one case the obviously "incorrect" values were confirmed by the respondents. This leads one to mistrust the accuracy of most replies.

The questionnaires have, however, lead to the following valuable findings:

- In several cases where respondents indicated that the beds were not performing adequately the poor performance could be traced to incorrect bed operation.

  Overloading of beds was the most common problem. This puts the emphasis on the need for training. Currently operators receive little or no training in the operation of drying beds (Basson, 1996, Small, 1997).

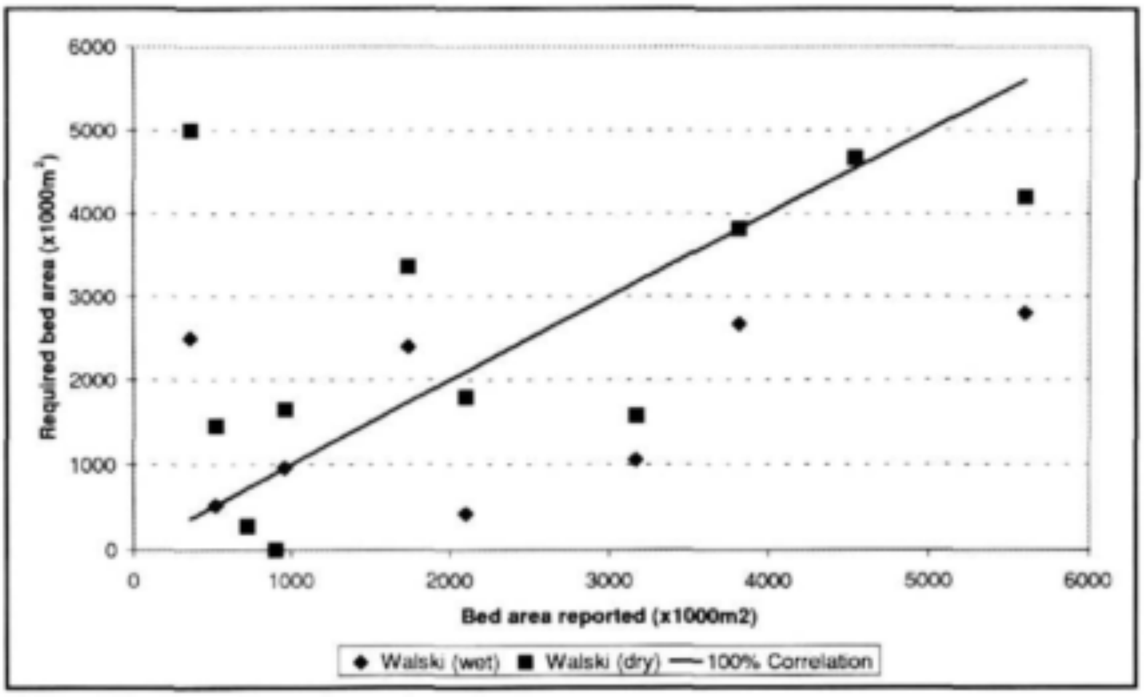


Figure 5.2 : Evaluation of questionnaire data

- The replies received, with some exceptions, were mainly from smaller municipalities and from plants with smaller capacities. This fact correlates well with interviews where operators reported intensive labour requirements to be one of their primary objections to the standard bed design. Larger municipalities and plants would therefore prefer not to make use of sludge drying beds.

- The questionnaires have emphasized the degree to which plant designs differ. This translates into differences in sludge character and also in the way sludge beds are utilised. This in turn emphasises the need for flexible design criteria, which has been requested by designers (Hoffman, 1996).

Table 5.2 (a): Data received from activated sludge plants (AS)

PLANT NO:	1	2	3	4	5	6	7
Qc m^3/d	2400	2847	1800	2200	2480	2200	6200
Qd m^3/d	4300	4152	2900	4000	4400	7000	6000
q_s m^3/d	20	18		50	594	25	
$\%S_o$ %	-40	63	38	75	3	-40	165
A m^2	72	55	75	200	264	180	640
A_T m^2	720	550	900	5600	3168	360?	5120
H_o m	2		24	25	225	14	
Td d	28	42	3	14	4	14	28
Tw d	28	70	10	21	6	28	56
A_w m^2	280		225	2800	1056	2500	
A_{Tw} m^2	280		750	4200	1584	5000	
A_T/q_s ($m^2/m^3.d$)	360	-	-	112	53	144	-

PLANT NO:	8	9	10	11	12	13
Qc m^3/d	5000	2700	?	3461	18000	950
Qd m^3/d	7500	4500	250	4000	26000	1500
q_s m^3/d	95			240	300	23
$\%S_o$ %	0,55	36		45	35	38
A m^2	110	120		240	8175	104
A_T m^2	2100	2400		2400	16350	520
H_o m	0,45				35	22
Td d	2	21		7	95	5
Tw d	8,5	35		9	30	14
A_w m^2	4220				38571	523
A_{Tw} m^2	1794				25714	1464
A_T/q_s ($m^2/m^3.d$)	221	-	-	10	681	226

Table 5.2 (b): Data received from biofilter plants (AD)

PLANT NO.	14	15	16	17	18	19	20	21
Qc m^3/d	5500	4000		1200	2800	10000	4400	17250
Qd m^3/d	5700	8100		3000	3400	15000	3100	16400
q_s m^3/d	500	318		179	24	50	20	
$\%S_o$ %	30	-40		70	-40	-40	-40	-60
A m^2	910?	127		96	97	328	24	4056
A_T m^2	47320	3816		960	1739	4539	4592	1296
H_o m	?	625		26	25	15	?	
Td d	20	21		14	25	14	7	21
Tw d	30	30		24	35	14	175	42
A_w m^2		2671		964	2400	4667		
A_{Tw} m^2		3816		1652	3360	4667		
A_T/q_s ($m^2/m^3.d$)	94.64	120		53.6	72.5	90.8	229.6	-

Table 5.2(c): Data received from combined plants (AS/BF)

PLANT NO:	22	23	24	25	26	27	28	29	30
Qc	11000	6477	23350	5500	54413			22000	6300
Qd	13100	7500	43333	23000	58200			29000	7000
AS/BF	16	20		36	53			66	15
q_s			40						
$\%S_0$	685		10	635	30				30
A	160	293	490	190	-238				
A_T	1440	3510	9800	1330	8806				
H_0									
Td	14	14	21	7	20				14
Tw	35	21	21	14	30				25
A_T/q_s	-	-	245	-	-			-	-

5.3 INTERVIEWS

5.3.1 Designers

In order to evaluate the various design approaches that are currently being employed in the construction of sludge drying beds, designers were interviewed. It appears that little variation exists and that the design is based on the following:

- The client indicates whether he prefers manual or mechanical means of sludge removal. In larger plants where sludge beds are employed, the mechanical methods are preferred.

- From the sludge type and amount of sludge produced, the bed is sized. This is generally done using fixed area per capita or area per sludge mass ratios. The effect of climate is not considered quantitatively in this exercise.

- The configuration of underdrains, floors, support media layering, wall construction, inlet and outlet facilities, etc. is normally based on the consultants' standard designs that have evolved over time.

- The placing of the beds in relation to the rest of the plant is based mainly on pumping and drainage considerations as well as the surrounding topography. Not all locations are, however, suited to the ideal placement of the beds and some compromises are inevitably required. In most cases very little can be done to improve this situation.

The designers approached to date are of the opinion that strict design guidelines are not appropriate as each plant is unique and requires some special considerations. This has been the case in the past with fixed "load per area" type guidelines. The designers have indicated that they want flexibility designed into the guidelines in order to allow them to exercise their judgement.

5.3.2 Plant operators

Following on the questionnaires many plant operators were contacted and telephonic interviews were held. In general there seems to be little enthusiasm among operators for sludge drying beds due mainly to the reasons mentioned previously, i.e. poor performance and labour difficulties. In many cases the operators make use of alternative sludge disposal methods such as sludge ponds or sludge irrigation although they may have beds available.

Where personal visits were made to plants, it was generally found that operators were aware of the existence of problems regarding drying bed management. Initiation of monitoring programmes has, however, received a low priority to date.

Addressing this situation is one of the main goals of the Guide and will be expanded in Chapter 7. The operators should be aware of the advantages sludge beds hold over other disposal procedures, for example in terms of ground water pollution control. This will become increasingly more important as the Department of Water Affairs and Forestry introduces increasingly more stringent requirements for the issuing of sewage treatment plant permits.

CHAPTER 6

GUIDELINES FOR DESIGN

6.1 GENERAL

There are two main aspects to be considered when designing sludge drying beds. The first of these is determining the total bed area (A_T) required (and the number of beds) and the second is the actual design detailing. In presenting this chapter the two groups have been separated. It must, however, be understood that certain considerations such as removal methods influence both aspects.

6.2 SLUDGE REMOVAL TECHNIQUES

In South Africa the removal of sludge from beds has traditionally been a labour-intensive operation. Due to increased labour cost, labour problems and the gradual increase in plant size and sludge removal requirements, more and more local authorities are considering using mechanical methods. Making the decision as to whether manual or automated methods should be used has, therefore, in most cases, been taken from the hands of the designer.

A decision can, however, still be made based on the basis of economy or efficiency and this is a complicated exercise. Mechanical methods are generally considered to be faster and more efficient than manual methods but they also require a higher capital outlay. Mechanical methods may also require structural alterations which may make the structure more expensive. On the other hand, manual methods are generally used on sand beds. The actual cost in sand can be high as this does need to be topped up periodically.

In short, capital, maintenance and operational costs should be considered when this type of analysis is done. Furthermore, this should be done on a design-by-design basis since so many variables are involved.

6.3 DETERMINATION OF BED AREA

As discussed in Chapter 2, 3 and 4, a number of design models have been presented that can be used in this exercise. These require various inputs on which the designer has to decide. It is important to remember that although the various parameters can be manipulated independently, the drying process is a function of all of the variables combined and that an alteration to the design might be advantageous seen from one aspect but might be a problem seen from another. A designer must consider various combinations of these parameters to optimise his design. The parameters are discussed separately below.

6.3.1 Depth of sludge application (H_0)

This parameter is normally fixed during design but in most cases the operator can try to optimise it by altering the operational procedure. As a treatment plant would normally deliver a fixed production of sludge mass, it would normally be optimised by altering the solids concentration (S_0), usually by passing the sludge through a thickening stage. As S_0 increases H_0 will therefore decrease (assuming a fixed bed area and mass of sludge). The opposite is also true. For this reason the sludge mass-per-area design guidelines have traditionally been used to determine H_0.

Sludge application depths of 200-300 mm on sand beds are considered to be the norm although many South African plants have been operating at up to 600 mm and more. These (600 sludge) beds normally do not dewater well. Several attempts have been made to determine optimal sludge application depths (Jennett and Harris, 1971). The results from these tests indicate a range of depths from 200-350 mm but these results are highly dependent on sludge characteristics that vary significantly. It is therefore suggested that each plant goes through continual optimisation exercises to determine these depths. Hoffman (1996) states that concrete floored beds should not be loaded deeper than 100-150 mm.

Randall and Koch (1968) studied the influence of H_0 on the drying time of aerobically digested sludge with constant solids content sludges and has shown that sludge applied at various depths initially drained at the same rate until virtually all the free water was exhausted. Thinner sludge applications therefore reached the end of their drainage phase sooner. As for the amount of water drained from each, it varied between 70 and 85% depending on the initial S_0 used. The application depth H_0 played no apparent role in the eventual solids concentration at the end of drainage (S_1). Although drainage time would be extended by using deeper applications, the drainage time is normally a small part of the total drying time and therefore has a limited influence. It would appear more economical, from a drainage point of view, to apply well conditioned sludges as deeply as possible. Seen in the light of the rest of the drying process, this could be counter productive. Vosloo (1978) found that a sludge cake which is half the thickness of a reference would dry out more than twice as fast. As a rule however, poorly digested sludges or sludges with poor drainage characteristics should be applied as thinly as possible. These include sludges with low sludge ages as well as those which contain filamentous organisms which inhibit dewatering (Randall and Koch, 1968).

6.3.2 Solids concentration (S_0)

Traditionally, activated sludges are applied at concentrations varying from 0,4% to 0,7%. When thickened these may range up to 4%. Anaerobic sludges are normally loaded at a S_0 of 3% to 4%.

The solids concentration is normally fixed by other process parameters and can only be altered by post-process thickening. It has already been stated that the sludge mass remains constant for a given plant. Should S_0 therefore be increased (with a fixed H_0), the total bed area required can be decreased. Randall and Koch (1968) found that aerobically digested sludges with higher S_0 at application, retained a larger percentage of water after drainage which would have a significant effect on subsequent drying time. This is expected to be true for other sludge types.

It is therefore recommended that sludges *not be thickened unless they are* well stabilized and have good dewatering characteristics. If sludges are to be thickened the application depths (H_0) should be kept low to avoid excessive rain water retention complications during the drying cycle.

6.3.3 Effective evaporation (aE-bR)

Walski (1976) proposed that "typical" wet month rainfall and annual evaporation is to be used in the determination of bed size. These two climatological conditions rarely occur simultaneously and also do not necessarily cater for the worst-case scenario.

As an example sludge beds on the highveld normally deliver their poorest performance during winter and best performance during summer. Using Walski's guidelines the designer would end up with beds sized for wet months (summer) and would therefore probably encounter problems during the dry months (winter).

Walski's guidelines were compared with other philosophies; these were:

(a) average annual rainfall (R_1) with average annual evaporation (E_1), referred to as R_1E_1;

(b) average rainfall over the three wettest months of the year (R_2) with the average evaporation for the corresponding period (E_2), referred to as R_2E_2; and

(c) average evaporation for the three lowest months of the year (E_3) and rainfall for the corresponding period (R_3), referred to as R_3E_3.

Walski's guidelines corresponds with a E_1R_2 combination.

Using values of 0,75 and 0,25 for a and b respectively, these philosophies were tested using the Walski model for low typical climatic conditions in South Africa. The net evaporation results from this exercise are given in Table 6.2.3.

Table 6.2.3 : Average effective evaporation values (aE-bR)

	R_1 (mm)	E_1 (mm)	Effective Evaporation (mm)	R_2 (mm)	E_2 (mm)	Effective Evaporation (mm)	R_3 (mm)	E_3 (mm)	Effective Evaporation (mm)	R_2 (mm)	E_1 (mm)	Effective Evaporation (mm)
Region 1 Winter rainfall	30	134	93	49	52	27	49	51	26	49	134	88
Region II Low summer rainfall High evaporation	4	159	113	41	193	135	11	76	54	41	160	110
Region III High summer rainfall Low evaporation	72	111	65	117	137	74	25	70	46	117	111	54
Region IV Medium rainfall Medium evaporation	47	138	92	84	175	110	11	77	55	84	138	83

From the table it appears as though R_3E_3 consistently describes the worst-case scenario which are significantly lower than that provided for by Walski (1976). It also becomes clear that extreme South African conditions are defined not by periods of high rainfall, but rather by periods of low evaporation.

It is therefore recommended that R_3E_3 be used in design if the beds are intended for use throughout the year. The designer can also repeat this exercise for shorter or longer dry/wet periods to investigate various scenarios. If the designer chooses to use alternative sludge dewatering techniques during adverse conditions, it would be up to him to determine what combination of rainfall and evaporation is to be used.

As an alternative the designer can consider limiting the effect of rainfall by covering the beds. This would increase the effective evaporation by removing R from the equation. This practice is common in other countries with wetter climates but is seldom used in South Africa. The cover (roof) should, however, allow sunlight to pass through as sludge does not dewater well in shade. Glass or fibre glass is generally used.

6.3.4 Solids concentration after drainage (S_1) and drainage time (t_1)

This is mainly a function of the character of the sludge and the designer has little influence here. It does, however, play a critical role in the Walski model and therefore in the determination of bed size.

As stated in Chapter 4 it is always preferable to determine S_1 and t_1 through laboratory analysis, but this is not always possible since samples of sludge are needed. These are not available when the plant is being designed. Because of this, an alternative approach was developed during the compilation of this guide. This is discussed in Chapter 4 and is demonstrated below.

Once the designer has fixed the application depth (H_0) and concentration (S_0), the sludge load (SL) can be calculated using the following equation (equation 6.2.4)

$$SL = \frac{H_0 S_0}{10} (kg/m^2) \qquad \text{............ 6.2.4}$$

Where H_0 is measured in cm and S_0 in %.

For example, say a well-stabilized activated sludge S_0 = 0,5 % is to be applied at H_0 = 30 cm, the sludge load (SL) would be 1,5 kg/m^2. The designer could, of course decide to start designing from the sludge load and then trace back to H_0 or S_0. S_1 can be determined from the empirically derived equation 4.3.4 (a) (for a well stabilised activated sludge).

$$S_1 = 22{,}8.SL^{-0{,}92}.S_0$$
$$= 22{,}8.(1.5kg/m^2)^{-0{,}92}.(0{,}5\ \%)$$

S_1 = 7,85 %

From this the tentative guidelines for estimating t_1 in Table 4.3.4 can be used. This indicates that the sludge mentioned above would dewater in less than one day. It is suggested that t_1 be taken as equal to 1 as this would allow a small margin of safety.

6.3.5 Solids concentration at point of removal (S_2)

S_2 can be varied according to the designer's needs. Generally sludges (activated and digested) are considered haulable (spadable) at S_2 = 40%. This value is then also suggested when manual labour removal techniques are considered. In some cases the sludges can be removed at much lower concentrations. At Erwat's treatment plant at Vlakplaas, for example, the digested sludge is removed at S_2 = 10-12% (Basson, 1996). In most cases this would not be possible but here a front-end loader is used and the bed has a concrete floor. It must, however, also be pointed out that the sludge takes approximately one month to dewater to this level. Ordinarily digested sludge would dry to 40% over a similar period of time on a sand bed.

6.3.6 Calculation of bed area and number of beds

Using the sludge defined above and also the S_1 and t_1-values that have been calculated, Walski's model can be used to calculate the bed area required. The model is stated below (equation 6.3.6). Assume a worst case scenario design as discussed in paragraph 6.2.3 with the average lowest evaporation over three months (E) equal to 15 cm/mo and with average rainfall over the same period (R) as 10 cm/mo. The a-factor is taken as 0,75 (refer paragraph 4.4) and the b-factor as 0,4 (refer paragraph 4.5.1).

$$A_T = \frac{100.qs}{H_0} T \text{ with}$$

$$T = t_1 + \frac{30H_0S_0}{aE - bR}\left(\frac{1}{s_1} - \frac{1}{s_2}\right) \qquad \ldots\ldots\ldots\ldots 6.3.6$$

Therefore

$$T = 1 + \frac{30(30cm)(0,5\%)}{(0,75)\ (15cm) - (0,4)\ (10cm)}\left(\frac{1}{(8,75\%)} - \frac{1}{(40\%)}\right)$$

= 6,54 d ≈ 7 days

As beds are filled and emptied on a daily basis T is rounded up to 7 days. For example, assume that the plant produces 100 m^3 of sludge per day (q_s) at 0,5 %, then the total bed area requirement would be:

$$A_T = \frac{100q_s\ T}{H_0} = \frac{100(100\ m^3/d)(7d)}{30\ cm} = 2333\ m^2$$

$$A = \frac{100qs}{H_0} = 333\ m^2\ per\ bed$$

If sludge is wasted on a daily basis, one bed would be needed for every day of the drying cycle. A further bed would be required to waste sludge to while cleaning is in progress in another which is in its seventh day of drying. A total of eight beds (each 333 m^2) would therefore be required in this case.

Should the sludge be thickened to 1% and applied 20 cm deep to increase S_0, the following is found:

q_s decreases to 50 m^3/d

SL increases to 2 kg/m^2

S_1 increases to 12,1 %

t_1 remains at 1 day

T increases to 7,4 days ≈ 8 days

A_T reduces to 2 000 m^2 and A to 250 m^2.

Allowing one additional bed for maintenance would mean that nine beds are required in this case. This can bring about a significant saving in capital cost, but can only be considered if the designer is convinced that the sludge will dewater acceptably.

Vosloo's (1978) design procedure is much simpler but the drying period cannot be determined from it. Vosloo bases this duration on past experience. He suggests a SL of 1,5 - 2,0 kg/m^2.

If 100 m^3 of sludge is produced per day at 0,5 % solids content, then (at 1.5 kg/m^2) the bed area required could be calculated as follows:

$$A = \frac{(100\ m^3/d)\ (5\ kg/m^3)}{1.5\ kg/m^2} = 333\ m^2$$

$$H_0 = \frac{1{,}5\ kg/m^2}{5\ kg/m^3} = 0{,}30\ m$$

This corresponds with the Walski approach. The difference, however, comes in when Vosloo (1978) states that the sludge will take approximately 4 days to dry, therefore

$A_T = A \times T = 333\ m^2 \times 4 = 1332\ m^2$

This is significantly less than the 2333 m^2 given by Walski's model. It is, however, unclear whether this is a worst-case design as with the Walski Model and can therefore not be compared directly. Vosloo also does not allow the designer to do a comparative study as Walski does since the drying time needs to be known.

Other sizing guidelines such as those of the Water Pollution Control Federation (WPCF) (Walski, 1976) work on a similar basis as Vosloo's. The daily sludge production of 100 m^3 at 0,5% solids deliver 500 kg of solids according to Lue-Hing *et al.* The production rate of sludge is 55 (g/cap.d). Therefore 9090 people would be required to produce 500 kg of sludge per day. WPCF allow 1-2 ft^2/cap.d, therefore 845-1690 m^2 will be required per day. There is no indication of what type of sludge is catered for or what the drying time will be. These results cannot be compared with Walski.

Using Vater's model (Adrian, 1978) the Gross Bed Loading (GBL) for the 0,5% sludge is 0,0109 kg/m^2.d. The Net Bed Loading (NBL) can be calculated (S_2 = 40%) (using equation. 2.4.2(c)). This is then equal to 0,0044 kg/m^2.d. The total drying time can then be calculated by making use of the solids load (SL) which is 1,5 kg/m^2 as calculated previously.

$$\frac{SL}{GBL} = T = \frac{1{,}5\ kg/m^2}{0{,}0109\ kg/m^2.d} = 138\ days$$

This does not compare well with Walski's 7 days or even Vosloo's 4 days. There are two possible reasons for this:

- Haseltine did this work on sludges with S_0-values ranging from 4 to 13%. Which lie substantially above the example used here (0,5%). Haseltine does therefore not cater for thin sludges.

- The model was developed from anaerobically digested sludges under American conditions. Although Haseltine (1951) does not give adequate information on climatic conditions, it is expected that these would be significantly different to South African conditions.

In conclusion it is recommended that Walski's model be used in design and that alternative models, especially those developed internationally, be discarded until they have been adapted for South African conditions.

6.4 PHYSICAL DESIGN CONSIDERATIONS

Once the size of the bed has been determined, the physical detailing can commence. Although all designers have some individual design preferences, some aspects are common. The various elements of a sludge bed are listed below and some points that could improve the design of the beds are highlighted.

6.4.1 Access to the bed

The decision made in terms of the method of sludge removal carries over into the physical design. If the sludge is to be removed manually not much is required apart from pedestrian access and that loading sludge from the bed to a wheelbarrow or trailer should not be unduly difficult. A front end-loader on the other hand would require a sloped access and the bed configuration should be such that the loader has access to all parts of the bed for effective sludge removal.

Should more elaborate mechanical removal techniques be considered such as permanently installed bridges and the like, the requirements of these systems should be borne in mind.

6.4.2 Ratio of bed length to bed width

A square or even round bed would be the optimum solution if cost were the only consideration. These shapes have better area-to-circumference ratios than the traditional rectangular beds. There are, however, a number of other aspects that should be considered and these are briefly expanded upon below.

(a) Sludge flow characteristics

Both digested and activated sludges will separate from the free water that carries them once they enter a stagnant situation. Fresh digested sludge contains gas bubbles which will force it to float while dead digested sludges (i.e. digested sludges that do not contain gas bubbles) and activated sludges tend to settle out. Because of this it is sometimes difficult to get an even distribution of sludge on a bed as sludge will tend to accumulate in thicker layers at the point of application. This could lead to a situation where one section of the bed takes significantly longer to dry than the other. This is more pronounced where thicker sludges are applied.

(b) Accessibility

If the bed is to be cleared using manual methods, the cleaner will have to move a fairly large volume of material to the wheelbarrow or trailer. It is advisable to keep this distance short to reduce double handling and to improve on productivity.

(c) Topography

It is sometimes necessary to construct beds on slopes. These beds would then be orientated to minimize the amount of earthworks and terracing required. A decrease in bed width would assist in this.

There are unfortunately no hard and fast guidelines available at present. The general trend, however, appears to be beds not wider than 6 -7 m and not longer than 30 - 40 m. There are, however, larger beds that operate successfully.

6.4.3 Floors, walls and drainage

The floors of a sludge bed can be constructed from concrete or can be excavated from the *in situ* material. The second option is the cheaper alternative but the designer must be aware of the following:

(a) The Department of Water Affairs and Forestry requirements in terms of the drainage water. In most cases the Department would insist on the water being returned to the process to avoid groundwater pollution.

(b) The nature of the *in situ* material. If the material has a significant clay content it will not drain well. The material may also become water-logged and complicate the sludge removal procedure.

(c) Over time the nature of the (*in situ*) material will change as it is contaminated by the sludge. It might loose its permeability and start hindering the drainage of water.

Because of these reasons it is advisable to have a strong, impervious floor - such as one constructed from concrete.

On a bed that will be cleaned manually, a concrete floor of approximately 75 mm thick would normally suffice as it would not need to carry high loads. These floors would generally be supplied with expansion and construction joints to ensure watertightness. On the other hand the floors that are intended to carry fairly heavy equipment such as front-end loaders would have to be designed to carry these loads. This implies thicker slabs with reinforcing.

Sludge bed walls can be constructed from bricks, concrete or earth embankments. The purpose of the walls is to contain the wet sludge when it is applied and should therefore also be of a watertight construction. Adequate freeboard is necessary above the sand or floor to contain the intended sludge level. Generally an additional 100-150 mm is allocated above the full sludge load. The walls must also protect the drying sludge from stormwater. A minimum wall height of 200-300 mm above the surrounding ground levels must be allowed for this purpose. If heavy equipment needs access one must ensure that the route does not allow stormwater to enter the bed. Furthermore the inside faces of the walls should be flush: Where brick walls are used the mortar should be finished flush with the brick to prevent dried sludge from clinging to the walls, and where heavy equipment is used to remove sludges, protrusions into the bed should be avoided to prevent damage to the walls.

As the drainage phase can rid the sludge of up to 75% of its water it is clear that adequate drainage facilities must be provided. In a sand bed the drainage has traditionally been placed under the media. Drainage can consist of a network of perforated pipes spaced 2,5 to 6 m apart. These could be vitrified clay or uPVC pipes. Lately these pipes have been replaced by drainage channels due to the relatively high breakage rate of the pipes. The channels are covered with bricks with a 5 to 8 mm spacing and overlain with coarse gravel. The floors are generally sloped toward the channels to facilitate the drainage process. The drains normally lead to an open sump. This facilitates cleaning and allows the operator a visible indication of what is happening.

The designer can also take advantage of the fact that sludge tends to separate from its free water. In activated sludge beds and beds that will take dead digested sludges, a structure can be incorporated to decant the supernatant as was suggested by Vosloo (1976). Vosloo's detail is presented in Figure 6.4.3. The most important feature of this detail is the ability to decant water from various levels, starting at the top and working down. This is to prevent the draw-off from scouring sludge from the bed's surface during the decanting process.

The main feature of this type of bed is that the whole end wall, opposite the inlet, is constructed as an overflow weir, with its top 300 mm above sand level and about 75 mm below the level of the other three walls. Downstream of the weir, a collecting trough is constructed which delivers the overflow into the underdrain system of the bed.

Upstream of the main overflow weir a second weir is constructed forming a channel about 150 - 300 mm wide between the two, running the full width of the bed. This channel has its floor about 50 mm below sand level and is divided into 5 troughs of equal lengths by means of short cross walls. Each trough can be drained by a 50 mm pipe and valve through the bottom of the main overflow weir, discharging into the main overflow collecting trough. The 5 sections of the upstream weir discharging into the 5 separate compartments, are of different heights, these heights being respectively 75, 120, 165, 210 and 255 mm above sand level.

Before filling all 5 valves will be closed. When full, clear water will decant over the main weir until the required bed load has been applied. The remaining surface water is then decanted by progressive opening of the valves from the highest to the lowest upstream weirs. Numerous variations around this principle are possible.

For anaerobically digested sludges a syphon arrangement can be included to draw the water from under the floating sludge. This works particularly well on beds where no media is used and no other drainage is facilitated as is the case with Vlakplaas (Basson, 1996).

6.4.4 Media

Media on a sludge bed performs as a support for the sludge and not as a filter as is commonly believed. The filtration is done by the sludge blinding layer which is formed when sludge is applied (Clewit and Handyside, 1976). The sand does, however, fulfil an important drainage function. Randall and Koch (1968) compared the drainage from a sand bed with that from a concrete floor with a centre drain and found that a 200 mm application on sand had drained and cracked after 8 hours while the application on the concrete floor still had a 25 mm layer of free water on the sludge after 10 days.

Typical specifications for sand lie in the order of d_{10} = 0,2 to 0,3 mm with a uniformity coefficient (UC) smaller than 4. (Palmer, 1988). The effective size or d_{10} size implies that 10% of the sample is smaller than this size. The uniformity coefficient is defined as d_{60}/d_{10}. The sand depth is normally specified between 150 mm and 300 mm (Palmer, 1988 and Anonymous, 1978). The sand is sometimes underlain by a coarse sand, fine gravel and coarse gravel layers (Vosloo, 1976). These layers are normally between 50 and 100 mm deep (Vosloo, 1978). No fixed guideline exists on the ratio of grain sizes between the various layers and there exists scope for further work in this regard as some of the layers can be expensive.

The top layer of sand should contain small grains to prevent sludge penetration into the beds. If sludges were to penetrate a substantial amount of sand would be lost every time sludge is removed. The sand would then have to be topped up more frequently. If, however, the media can be procured cheaply or for free, the penetration of sludge would not be such a big problem. The Daspoort treatment plant at Pretoria uses ash which it collects from a local power plant at no cost (Saayman, 1995). Although their media losses are quite high, this does not present them with a problem.

It is generally accepted that the media cannot support heavy equipment, and therefore is not used when automated sludge removal is intended. The American experience has been that the concrete floor beds did not dewater well, even though drainage channels were provided (Randall and Koch, 1968). Subsequently concrete slabs or runners were provided so that the equipment could run on these, but this also did not work well (Banks and Lederman, 1990).

These tracks limited the access of the equipment and also decreased the effective drainage area.

Banks and Lederman (1990) suggested a high-density polyethylene cellular confinement system that was placed in the media. The hexagonally shaped tubes extended the full depth of the top layer. The system provides the media with structural support by preventing lateral slippage or shear of the confined material. In addition to allowing a small front-end loader access to the bed it also provided a handy reference for sludge removal as it prevented the loader from removing excessive amounts of sand.

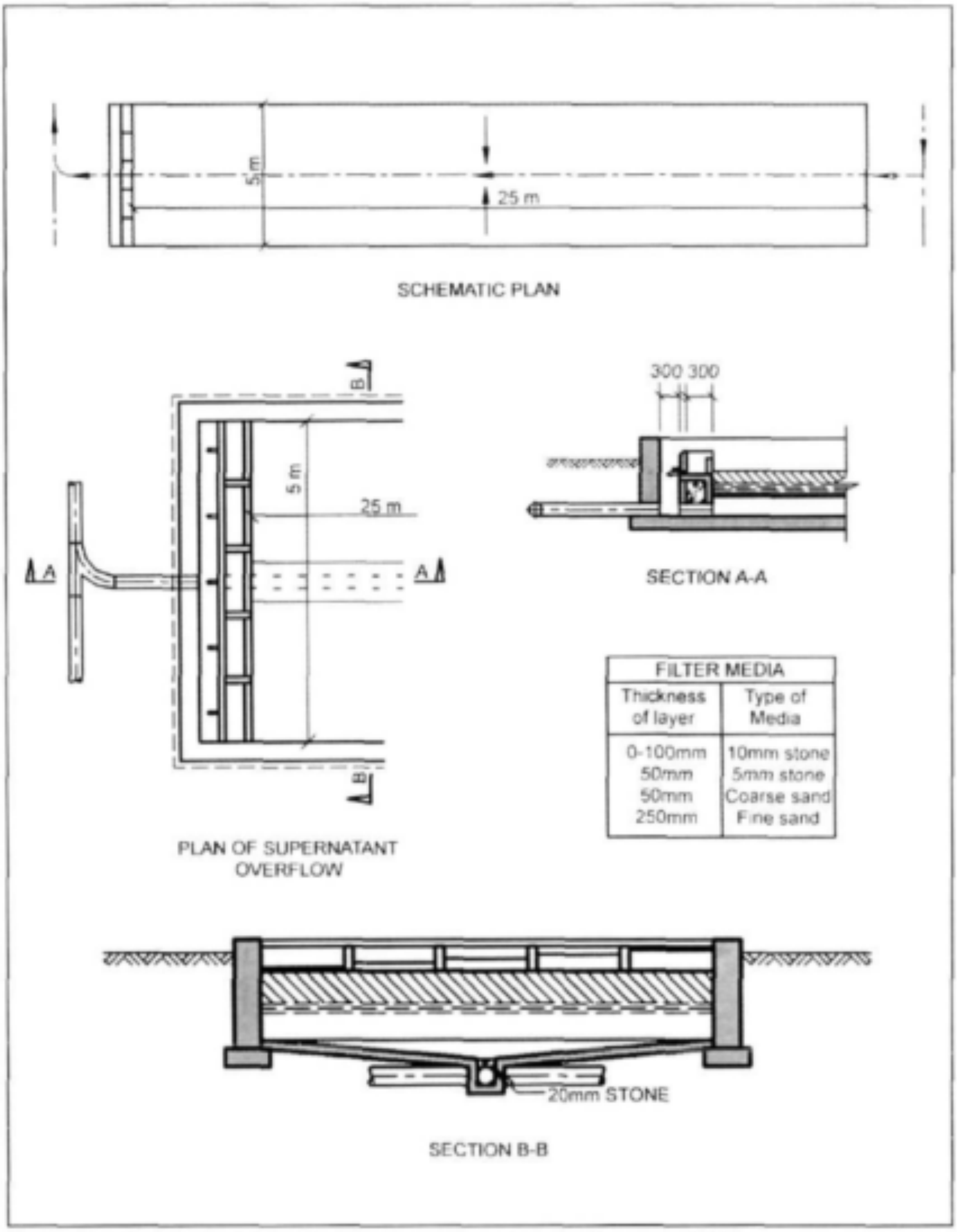
Another alternative (Anon, 1975) would be to use a small track-type loader as opposed to a balloon-wheeled loader. The wheel loader tended to press down on its front wheels whereas the track type loader distributed its load over its entire track.

6.4.5 Sludge application methods

The method of sludge application is fairly standard. Each bed is provided with an outlet through which the sludge is pumped into the bed. The inlet normally points into a stilling basin which prevents the flow from disturbing the media surface.

6.4.6 Bed placement and alignment

It has been mentioned previously that beds are often constructed against slopes. In most cases the optimisation of earthworks and minimisation terracing will dictate the beds' alignment. It is, however, important to bear in mind that sludge beds that are not exposed to direct sunlight will dewater poorly. This would imply that beds should not be constructed on steep southern slopes, or close to other structures or trees that might cast a shadow on the beds. Even sludge bed walls cast shadows that prevent portions of the sludge from dewatering. This is especially true for beds with a direct east-west alignment where the sludge against the northern wall will be in shade all day during winter. This sludge does not dry out. The optimum alignment has been found to be northeast-southwest or northwest-southeast. With such an alignment the entire bed will be exposed to direct sunlight at some point during the day.



FILTER MEDIA	
Thickness of layer	Type of Media
0-100mm	10mm stone
50mm	5mm stone
50mm	Coarse sand
250mm	Fine sand

Figure 6.4.3 : Typical activated sludge bed design by Vosloo (1978)

A further consideration is the placement of the beds in relation to the rest of the plant. Sludge can either be delivered by gravity onto beds or pumped there. This would mean that the supernatant and filtrate would be pumped back or drained back respectively. The second alternative is preferred as it allows more control over the sludge wasting procedure.

CHAPTER 7

OPERATIONAL GUIDELINES

7.1 GENERAL

The operation of a sludge drying bed is essentially a simple exercise. It is however crucial to the success of any bed design, as poor operational procedures would turn the best designs into failures. A common misconception is that the operation consists only of the application and removal of sludge, while maintenance and optimisation are often neglected.

7.2 APPLICATION OF SLUDGE

Sludge applied to drying beds must be stable and should be applied in depths that will dewater adequately. Overloading a sludge bed could lead to extended dewatering cycles due to slower evaporation from the sludge cake and also increased water retention after rain. Furthermore, new or fresh sludge should not be placed over dried or partially dried sludge. This would have an effect similar to overloading the bed. It would be preferable to remove the partially dried sludge and to spread it over a slab or clearing to continue with its drying cycle if bed area is urgently required for fresh sludge.

7.3 REMOVAL OF SLUDGE

The timeous and regular removal of sludge seems to be the largest problem encountered by plant operators. Sludge should be removed immediately after it has reached its required solids content level. It is always the preferred situation to have beds spare than to have to make difficult decisions because no beds are clean or ready to accept sludge. This is valid for plants where mechanical as well as labour-intensive methods for sludge removal are employed.

Many plant operators state that their removal difficulties stem from poor performance by labour. This problem could possibly be overcome by the employment of day labour or task labour to fulfil this function. Different labourers can be employed every day and their payment can be based on the amount of work done rather than on a fixed wage. This management principle has been employed successfully by some municipalities. Consideration can even be given to contracting this function to a member of the local community who would in turn also appoint other people from the community. Payment to the contractor should be made on a performance basis.

Important aspects of sludge drying bed maintenance are the raking and levelling of the bed. Water that drains from sludge will cement media particles. This will lead to increased resistance to filtration in the media and eventually blockage thereof. During site visits made in the course of the compilation of this guide, empty sand beds were encountered that retained rainwater on the surface. These beds then act as beds with no drainage facility. Beds should be scarified and raked to a depth of 100 mm after every drying cycle to prevent this from happening. This is not such a time-consuming procedure as one would think. Long nails driven through a plant at regular intervals could be weighed down and pulled by hand across a bed. Two or more of these in tandem one behind the other should be adequate. This must, however, be done after every clearing exercise.

Levelling is necessary to allow the sludge to settle in an even layer across the bed. Beds are often scoured out in the centre or around the application point. This allows a thicker depth of sludge to settle there, which will take much longer to dewater sufficiently. The raking exercise described above would also fulfil a levelling function. It might, however, be necessary to do some finishing work.

7.4 OTHER MAINTENANCE ASPECTS

The walls and floors of beds will need to be inspected regularly and maintained. Cracks that form due to settlement or for any other reason should be repaired as soon as possible to prevent leakage of sludge or drainage water. Unwanted plant growth around structures should be removed to prevent damage to the structure and access ways and to avoid shadows on the sludge.

7.5 RECORDS

In order to assess the performance of sludge drying beds it is necessary to maintain a complete record of the activity on every bed. These records must contain the following:

- sludge application date,
- sludge application thickness (H_0),
- solids concentration at application (S_0),
- sludge removal date and length of drying cycle (T),
- solids content at removal (S_2),
- rainfall record, and
- notes on other factors that might influence the bed's performance.

These records will assist in the early identification of problems, as they will make it easy to trace trends in bed performance and will also assist in the design of extensions to the plant.

7.6 PERFORMANCE OPTIMISATION

Despite the fact that operational procedures need to be fixed during design, the operator will, in most cases, have the ability to vary these parameters to some degree. The parameters include:

- sludge age,
- solids content at application (S_0), especially if a sludge thickening process step is provided before the sludge beds,
- sludge application depth (H_0), and
- solids concentration at removal (S_2).

The impact of these parameters changes on bed performance can be measured using Haseltine's (1951) GBL and NBL concepts as is illustrated below.

Assume from the example in paragraph 6.3.6 that 8 beds of 333 m^2 each have been provided for the activated sludge (0,5% S_0) and that the sludge dries on average over 7 days according to the operator's records. The sludge is removed at S_2 = 40%. The values for GBL and NBL would then be:

$$GBL = \frac{H_0.S_0}{T} = \frac{(100\ kg/m^3)(0,3\ m)(0,5\%)}{7d} = 0,214\ kg/m^2.d$$

$$NBL = GBL.S_2 = 0.214\ kg/m^2.d \times 40\% = 0,086\ kg/m^2.d$$

Assume the plant operator decides to thicken the sludge and he applies the sludge at 1% (S_0). His records indicate that the sludge dries in 8 days. The dewatering of the sludge prior to application has decreased the sludge volume to 50 m^3. The sludge application depth (H_0) is now 50 m^3/233 m^2 = 0,215 m and the corresponding GBL and NBL are

$$GBL = \frac{(1000)(0,215)(1,0\%)}{8} = 0,269\ kg/m^2.d$$

$$NBL = 0,269\ kg/m^2.d \times 40\% = 0,108\ kg/m^2.d$$

Comparing the GBL and NBL values for the two scenarios the operator can now see that the sludge drying rate is higher if the sludge is applied after it has been thickened. He can now investigate the effect of varying other parameters which could result in saving both time and money. He could then also be in a position to assist the designer in determining what additional bed area is required when the plant is expanded.

7.7 MEDIA

The media used on some drying beds can be very expensive. Operators should endeavour to identify possible media sources and alternative media types in the proximity of the plant. The alternative media sources can be tested by topping up the existing media over 10-20 m^2 sof bed area. A comparison can then easily be drawn between the existing media and any new sources and also what alternative procedures should be considered.

7.8 HEALTH ASPECTS

Sludge applied to drying beds will always contain viable organisms that will expose workers to some risk. This is the same anywhere else on a treatment plant. The workers should therefore be informed and educated in these matters. Labourers working in or around sludge beds must at the very least be provided with gumboots and gloves which should be kept clean.

7.9 CRISIS MANAGEMENT

It is difficult to give precise guidelines on crisis management as problems that arise on a plant can normally be traced to inadequate bed space or improper operation. Operational difficulties normally manifest themselves over a period of time and can normally be identified timeously if a proper log of bed operation is kept. These problems can then be solved at the source through investigating various operational alternatives. If the bed area still proves to be insufficient after this, additional beds will have to be constructed. As an alternative the application of coagulants can be considered to improve the sludge's dewatering characteristics. Vosloo (1978) has, however, stated that the application of coagulants does not really improve the dewatering time of well-stabilized sludges. If this route is considered, a detailed investigation must be made to compare the initial capital cost of additional beds with the increased long-term expense of applying coagulants.

CHAPTER 8

RESEARCH NEEDS

8.1 SURVEYS

During the compilation of this guide an effort was made to retrieve practical information on design and operational parameters by distributing questionnaires to a number of authorities using drying beds. The feed-back was highly unsatisfactory in that no logical pattern could be found in the data. This endorses the need for accurate surveys.

8.2 VALUES FOR t_1 AND S_1

The basis of the manual was essentially to use the Walski model for design purposes. Limited experimental work was conducted with some activated and anaerobically digested sludges. The limited results were subjected to regression analysis to estimate:

(a) drainage time (t_1), and

(b) solids concentration after drainage (S_1).

It is evident that regression equations should be further refined. It is recommended that further work be done in this regard.

8.3 RELATIONSHIP BETWEEN S_0, S_1 and SL

An important contribution made in this study was to show the relationship between the solids concentration at application and after drainage (S_0 and S_1) and solids load (SL), which is:

$$\frac{S_1}{S_0} \alpha \ SL$$

This relationship was empirically quantified for well-digested activated sludges, poorly digested activated sludges and anaerobically digester sludges. These relationships should be verified further with much larger data sets and could be quantified for other sludges.

8.4 FURTHER DEVELOPMENT OF MEDIA SPECIFICATIONS

As stated previously, the media used in sand beds contribute towards a large portion of the capital outlay, yet no guidelines on this exists. Three of the most important questions that need to be answered are:

(a) What is the optimum grain size and grain size distribution for sludge bed applications and what are the results if the designer moves away from these optimum points.

(b) What should the ratio be for grain sizes and size distributions between various levels of media to ensure long-term stability of the media layers while at the same time allowing the designer to use the least number of sand layers.

(c) Other media types and sources.

8.5 SLUDGE BED SIZE LIMITATIONS

No clear guidelines could be found on the optimal size and shape of sludge depths. Sludge will settle irregularly over any bed due to the separation of sludge from the water carrying it. Should the bed be too long, sludge will settle in a thick layer on the entrance side of the bed and no sludge will be carried to the draw-off side. It is not clear at this point what the maximum dimensions should be. Further work could be done in this regard.

8.6 SLUDGE PRODUCTION

Appreciable scope remains for prediction of sludge fluxes for various types of sewage works design. This should be based on raw sewage quality and parameters relating to process design and operation.

LITERATURE CITED

1. Adrian DD (1978) *Sludge dewatering and drying on sand beds.* US EPA Report No. EPA -6002 - 78-141.

2. Anonymous (1975) Sludge removal from drying beds. *Public Works Jnl.* Nov. p. 64

3. Anonymous (1977) Sludge dewatering - a task the right equipment makes easier. *The American City & County,* p.49.

4. Banks JA and Lederman WK (1990) Innovative sludge drying bed design. *Public Works Jnl.* Sept. p.112.

5. Barnes D, Bliss PJ, Gould BW and Valentine HR (1981) *Water and Watewater Engineering Systems.* The Pitman Press, Bath.

6. Basson H (Jnr) (1996) Erwat, Pers. comm.

7. Basson H (Snr) (1996) Erwat (Retired), Pers. comm.

8. Clewett MA and Handyside RN (1976) Asphaltic concrete sludge drying beds. *Water.* **3** (3) pp.15-17.

9. Department of Environmental Affairs, Weather Bureau (1988) *Climate of South Africa, Climate statistics up to 1984.* Pretoria.

10. GFJ (Pty) Ltd. (1999) Working Papers to "Guidelines for the design and operation of sewage sludge drying beds", Pretoria.

11. Haseltine TR (1951) Measurement of sludge drying bed performance. *Sew. & Ind. Wastes,* September, pp. 1065-1083.

12. Hoffman R (1996) Wates Meiring Barnard, Pers. Comm.

13. Jacke R (1976) Polymer cuts disposal costs. *Water & Sew Wks.* p.99.

14. Jennett JC and Harris DJ (1971) *Environmental factors in design and operation of waste water sludge drying beds.* Missouri Water Resources Research Centre, University of Missouri-Rolla.

15. Lue Hing C, Zeng DR and Kuchenvither R Municipal (date unknown) *Sewage sludge management: processing, utilization and disposal.* Technomic Publishing Co. Inc., Lancaster.

16. Macaulay RA (1976) Chemical conditioning of sludges. *Workshop session on sludge dewatering as treatment.* Inst Water Pollut Contr S. Afr. Branch, Durban. pp. 1-8.

17. Marklund S (1990) Dewatering of sludge by natural methods. *Water Sci.Tech.* **22** (3,4). pp. 239-246.

18. Mignone NA (1977) Survey of anaerobic digestion supernatant treatment alternatives. *Water & Sew. Wks.* p. 42.

19. Novak JT and Langford M (1977) The use of polymers for improving chemical sludge dewatering on sand beds. Ind. Waste Conf, 30 th, Purdue Univ., Ann Arbor Sci. Pub. pp. 94-106.

20. Ohara GT, Raksit SK and Olson DR (1978) Sludge dewatering studies at Hyperion Treatment Plant. *Journal WPCF*. May. pp. 912-925.

21. Palmer I (1985) Some options for the treatment of alum sludges. Paper presented at the Biennial Conference of the IWPC, SA Branch. pp. 1-11.

22. Palmer I (1988) Sludge drying beds. WISA Sludge management working group seminar, Min. Trade fair.

23. Pitman AR (1975) Bioflocculation as means of improving the dewatering characteristics of activated sludges. *Water Pollut. Contr.* **74** (6) p. 688.

24. Randall CW and Koch CT (1968) *Drying characteristics of aerobically digested sludge*. National Technical Information Service, Springfield, Va.

25. Saayman G (1995) Pretoria Town Council, Pers. comm.

26. Schmidtke NW (1978) Sludge thickening, conditioning and dewatering. *Canada Ontario Agreement on Great Lakes water quality, Conference Proceedings.* **6** Canada EPA, Ottowa. pp.173-216

27. Small A (1997) Technisa lecturer, Pers. comm.

28. Smollen M (1986) Dewaterability of municipal sludges 1 : A comparative study of specific resistance to filtration and capability suction time as dewaterability parameters. *Water SA* **12** (3) p.127.

29. Smollen M (1986) Dewaterability of municipal sludges 2: Sludge characterisation and behaviour in terms of SRF and CST parameters. *Water SA* **12** (3) p.133.

30. Smollen M (1988) Moisture retention characteristics and volume reduction of municipal sludges. *Water SA* **14** (1). p. 25.

29. Swanwick JD, Lussignea FW and Baskerville RC (1964) Recent work on the treatment and dewatering of sewage sludge. *Advances in Water Pollution Control*, **2**. Pergamon Press, pp. 387-417.

30. Vosloo PBB (1978) Design of drying beds for activated sludge. *Water Pollut. Control*. p.71.

31. Walski M (1976) Mathematical model simplifies design of sludge drying beds. *Water Sew. Wks. Jnl.* April, p.64.