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Oppervlaktedelfstoffen in Nederland

Geologisch aanwezige, technisch winbare en planologisch winbare voorraden

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Inhoudsopgave

1 Inleiding

1.1 Doelstelling en definities

Dit rapport geeft voor beleidsdoeleinden inzicht in de beschikbaarheid van oppervlaktedelfstoffen in de Nederlandse ondergrond. Oppervlaktedelfstoffen zijn delfstoffen die worden gebaggerd of in dagbouw ontgonnen. In Nederland worden ze voor het overgrote deel gewonnen als bouwgrondstof of de productie daarvan. Bouwgrondstoffen zijn minerale bulkgrondstoffen[1] die worden toegepast in de grond-, water- en wegenbouw (GWW) en burgerlijke en utiliteitsbouw (B&U), waaronder:

- granulaten[2] zoals zand, grind en steenslag;
- klei;
- natuursteen, die niet alleen wordt verwerkt tot steenslag maar ook wordt toegepast als bouwsteen.

Er komen in Nederland een paar oppervlaktedelfstoffen voor die niet, of niet exclusief in de bouw worden toegepast:

- In Zuid- en Oost-Nederland komt zeer zuiver kwartszand voor dat in de procesindustrie wordt gebruikt als grondstof voor glas, keramiek en—indien zeer zuiver—voor optisch glas en glasvezel voor elektronica en telecommunicatie.
- In Oost-Nederland wordt op bescheiden schaal kalkgesteente gewonnen voor toepassing als kalkmeststof, vulstof, calciumbron in veevoer en magnesiumbron in kunstmest.
- Historisch is er op grote schaal veen in Nederland gewonnen als huis- en industriële brandstof.

De termen oppervlaktedelfstof en bouwgrondstof worden vaak door elkaar of als synoniem gebruikt, maar delfstof verwijst naar het materiaal zoals dat in de natuur voorkomt, terwijl grondstof verwijst naar het materiaal zoals dat wordt toegepast na eventuele bewerkingsslagen. Oppervlaktedelfstof is overigens een typisch Nederlandse beleidsterm, die niet met een geologische of industriële categorisering correspondeert en internationaal ook niet gangbaar is. De grondslag is wettelijk: oppervlaktedelfstoffen vallen onder de Omgevingswet (voorheen in de Ontgrondingenwet) en diepe[3] mijnbouw—de winning van gas, olie, steenzout, aardwarmte en voorheen kolen—onder de Mijnbouwwet. Om oppervlaktedelfstoffen te winnen is een ontgrondingsvergunning nodig die wordt afgegeven door Rijkswaterstaat of de Inspectie Leefomgeving en Transport voor de Rijkswateren, en elders door de provincies. Verder is er een omgevingsvergunning nodig die wordt afgegeven door de gemeenten.

[1] Metalen die eveneens veel in de bouw worden gebruikt voor bijvoorbeeld betonwapening en bekabeling worden overigens niet tot de bouwgrondstoffen gerekend.
[2] Granulaat—materiaal in korrelvorm—wordt hier gebruikt als vertaling van de Engelse term *aggregate*. In een smallere betekenis verwijst de term uitsluitend naar gebroken materialen zoals betongranulaat of steenslag.
[3] Diep wil zeggen dieper dan 500 m voor aardwarmte en dieper dan 100 m voor andere hulpbronnen.

1.2 Geologie, toepassing en voorziening

1.2.1 Granulaten

Natuurlijke granulaten, met name zand, komen veel voor in de ondiepe Nederlandse ondergrond. Om geologische redenen neemt de korrelgrootte ruwweg van het zuidoosten naar het noordwesten af. Grindafzettingen komen met name voor in Limburg. Grof zand wordt vooral aangetroffen ten zuidoosten van een denkbeeldige lijn van Terneuzen naar Delfzijl. In de kustprovincies en op de Noordzee komt vooral fijn zand voor.

De vuistregel is: hoe grofkorreliger, hoe geavanceerder de toepassing. Fijn zand wordt zonder noemenswaardige verdere bewerking gebruikt voor ophogingen, funderingen en kustsuppleties. Grof zand wordt in gebonden toepassingen gebruikt zoals beton en asfalt. Door middel van zeven en classificeren worden er specifieke producten vervaardigd zoals betonzand, asfaltzand, metselzand en kalkzandsteenzand, elk met specifieke eisen aan de korrelverdeling. Deze producten komen dus niet als zodanig in de natuur voor, wat betekent dat er bijvoorbeeld strikt genomen niet kan worden gesproken van beton- of metselzandvoorkomens. Door de industrie wordt op basis van met name korrelgrootteanalyses aan boormonsters bepaald welke producten er op een specifieke locatie kunnen worden geproduceerd. De winbaarheid hangt af van de dikte van eventueel aanwezige dek- en tussenlagen van klei/en of veen: zijn die te dik, dan is zandwinning onrendabel dan wel onmogelijk.

Grind en steenslag worden eveneens met name in gebonden toepassingen gebruikt. Hiervoor kunnen er, naast eisen aan de korrelverdeling, ook criteria bestaan voor de korrelvorm, -samenstelling en -sterkte. De vuursteen die in Maasgrind voorkomt kan bijvoorbeeld niet worden gebruikt in gewapend beton dat wordt blootgesteld aan zout water: dat kan leiden tot alkali-silicareacties (‘betonrot’). In hogesterktebeton of als spoorballast wordt hoekige steenslag toegepast die is vervaardigd uit een hard gesteente. Lastig aan grind in de context van bouwgrondstoffen is dat in de geologie de grens tussen de grind- en zandfracties wordt gelegd bij 2 mm en in de industrie bij 4 mm. Wat in de geologie wordt gezien als fijn grind, heet in de industrie grof zand.

Het verbruik van granulaten in Nederland bedraagt ruim 130 miljoen ton per jaar. Het gaat om circa 20 miljoen ton per jaar aan grove granulaten (grind en steenslag), waarin voor ongeveer een kwart wordt voorzien met binnenlandse winning van grind. Het verbruik van industriezand (betonzand, metselzand en kalkzandsteenzand) is iets lager. Hierin is Nederland netto zelfvoorzienend: er wordt ongeveer 5 miljoen ton per jaar geïmporteerd (vooral uit Duitsland) en 5 miljoen ton per jaar geëxporteerd (vooral naar België). Nederland wint en gebruikt ongeveer 45 miljoen m^3 (65 miljoen ton) per jaar aan ophoog- en suppletiezand. Als er sprake is van een bijzonder project, zoals de aanleg van de Tweede Maasvlakte of de Zandmotor, dan kan het zandverbruik omhoog schieten. Tot slot wordt er 30 miljoen ton per jaar aan secundaire granulaten gebruikt, voor ophogingen en aanvullingen, als funderingsmateriaal of als grindvervanger in gebonden toepassingen. Voor meer details over de voorziening in granulaten wordt verwezen naar Van der Meulen et al. (2025; bijlage 1).

Van der Meulen et al. (2005; bijlage 2) berekende dat de technisch winbare hoeveelheden grof zand in Nederland zeer groot zijn in relatie tot winning en verbruik, maar dat grind schaarser voorkomt, zowel in vergelijking met zand als in relatie tot het verbruik. In deze rapportage wordt in aanvulling hierop gekeken naar planologische winbaarheid, waarin rekening wordt gehouden met de toegankelijkheid van de voorraden, in relatie tot landgebruik en een eventuele beschermde status zoals Natura2000.

1.2.2 Overige grondstoffen

Klei wordt op een in verhouding tot zand bescheiden schaal gewonnen als grondstof voor de dakpan- en baksteenindustrie, de dijkverzwaring en de afdichting van stortplaatsen e.d. Bij een winning van ca. 1,5 miljoen m^3 per jaar is de door Van der Meulen et al. (2007; bijlage 3) berekende winbare voorraad van 15 ± 5 km^3 aan technisch winbare klei dermate groot dat klei als geologisch niet-schaars kan worden aangemerkt, ook al is op basis van geologische gegevens niet te bepalen welk aandeel van de totale voorraad geschikt is als keramische grondstof. Bovendien wordt klei op de uiterwaarden afgezet in hoeveelheden die de winning benaderen (Van der Meulen et al. 2009; bijlage 4); klei is tot dus op zekere hoogte als hernieuwbare grondstof aan te merken.

Na de hoogwaters van 1993 en 1995 werd er in 1995 en 1996 een totaalvolume van ruim 7 miljoen m^3 gebruikt in het dijkversterkingsprogramma Deltaplan Grote Rivieren (bijlage 3, figuur 18.14). Gedurende die twee jaar werd er ongeveer zes keer zoveel klei voor overige (niet-keramische) toepassingen gewonnen als tot dan toe. Als het totaalverbuik voor het Deltaplan Grote Rivieren maatgevend is voor eventuele toekomstige dijkversterkingsmaatregelen in relatie tot klimaatverandering, gaat het nog altijd om geringe volumina in vergelijking met de totale hoeveelheid klei in de ondiepe Nederlandse ondergrond. Van klei voor dijkverzwaring mag bovendien worden aangenomen dat een veel groter aandeel van de geologische voorraad geschikt is dan van klei voor de keramische industrie. Dit rapport gaat dan ook niet in op de planologische winbaarheid van klei.

Zilverzand kent een vergelijkbare verhouding tussen winning (300 à 400 duizend m^3 per jaar) en de totale voorraad die door Van der Meulen et al. (2009; bijlage 5) is geschat op 10 ± 5 km^3. Omdat de voorkomens van zilverzand echter meer gelokaliseerd zijn dan die van klei, werd in het betreffende artikel aangeraden om er rekening mee te houden in de ruimtelijke ordening teneinde sterilisatie—ontoegankelijk maken voor winning door bijvoorbeeld bebouwing—te voorkomen.

Kalksteen – In Oost-Nederland en Limburg komen kalkgesteenten voor die op bescheiden schaal worden gewonnen voor de productie van kalkpoeder, dat op zijn beurt wordt gebruikt als kalkmeststof in de landbouw, als vulstof in verschillende industrieën en voor de rookgasontzwaveling. De Limburgse mergel werd tot voor kort gewonnen voor de cementproductie, maar op dit moment slechts op zeer bescheiden schaal als bouwsteen voor restauratiewerkzaamheden. Deze rapportage gaat niet nader op voorraden en winbaarheid van kalksteen in.

2 Gegevens en informatie

2.1 Zand en grind

De Geologische Dienst Nederland (verder GDN) beschikt in de databases DINO en BRO over honderdduizenden boormonsterbeschrijvingen. Hierin wordt zand geclassificeerd op basis van de zandmediaan, d.w.z. de statistische mediaan van de korrelgrootteverdeling van het zandmonster in kwestie. De mediaan of de klasse kan visueel zijn geschat of—in een minderheid van de gevallen—gebaseerd op zeving of meting. In elk geval is er meestal minimaal een semikwantitatieve schatting van de korrelgrootte van boormonsters beschikbaar, die kan worden gebruikt als basis voor een opbrengstschatting van bouwgrondstoffen.

In tabel 1 is aangegeven wat het aandeel is van zand in vier korrelgroottebereiken (de oppervlaktedelfstof) dat kan worden verwerkt in drie productbereiken (de bouwgrondstof): alle zand en grind, zand 0-1 en grover, en zand 0-4 en grover. Voor 'Alle zand en grind' zijn de opbrengstpercentages voor alle korrelgroottebereiken 100%. Voor zand 0-1 en grover en zand 0-4 en grover wordt niet alles verwerkt en is de opbrengst van de verschillende korrelgroottebrereiken 0, 50 of 100%. In bijlage 2 is uitgelegd dat een meer gesofisticeerde omrekening, gezien de aard van de gegevens, tot schijnprecisie zou leiden. De omrekenmethode is destijds door de industrie getoetst.

Tabel 1. Theoretische hoeveelheden bouwgrondstoffen in drie productbereiken die kunnen worden geproduceerd uit zand (en grind) in situ in vier korrelgroottebereiken, cf. omrekeningsfactoren in Van der Meulen et al. (2005; bijlage 2).

Mediaan (µm)	Opbrengst (%)		
	Alle zand en grind	Zand 0-1 en grover	Zand 0-4 en grover
<105	100	0	0
105–210	100	50	0
210–420	100	100	50
>420	100	100	100

Sinds 2005 maakt de GDN op basis van boor- en andere gegevens opbrengstmodellen voor zand- en grind, eerst een lageresolutiemodel als *proof of concept*, vervolgens een voor het informatiesysteem *Delfstoffen Online*, dat telkens wordt geüpdatet als er nieuwe modelgebieden van het BRO-model GeoTOP beschikbaar komen. Maljers et al. (2015; bijlage 6) geven de nadere details van de verschillende modellen[4].

[4] Op het moment van oplevering van het voorliggende rapport staat de GDN op punt om updates uit te brengen van zandopbrengstmodellen voor de GeoTOP-gebieden Zeeland and Noord-Brabant en Noord- en Midden-Limburg. De opbrengstschattingen zullen enigszins afwijken van de modellen die voor hfdst. 3 gebruikt zijn. Er is echter besloten om het rapport niet te actualiseren. Het GeoTOP Oost-Nederland is namelijk nog niet afgerond; het is ons inziens beter om de winbaarheid in het zandrijke zuid- en oost-Nederlandse provincies op dezelfde grondslag met elkaar te vergelijken.

2.2 Klei

De geschiktheid van klei voor de grofkeramische industrie hangt af van eigenschappen die niet standaard worden bepaald of gemeten aan geologische, hydrogeologische of geotechnische boormonsters waarvan de gegevens in databases van de GDN zitten. Bij afwezigheid van voldoende geschikte gegevens hebben Van der Meulen et al. (2009; bijlage 3) niet de geschiktheid, maar de ongeschiktheid van klei voor deze toepassing bepaald. Voor meer informatie wordt verwezen naar bijlage 3.

2.3 Zilverzand

De toepassingsmogelijkheden van zilverzand hangen met name af van de zuiverheid. Hierbij gaat het zowel om het gehalte korrels van andere mineralen dan kwarts als om huidjes (‘coatings’) van bijvoorbeeld ijzer(hydr)oxiden om kwartskorrels. Voor meer informatie wordt verwezen naar bijlage 5 (Van der Meulen et al., 2009).

3 Resultaten zand en grind

3.1 Nederland excl. Noordzee

Zand en grind worden in het landgebied vooral gebaggerd, maar kunnen ook in groeves worden gewonnen. Het dieptebereik van zandwinning is in de praktijk maximaal ~30 meter. Onderstaande opbrengstschattingen zijn tot deze diepte onder het maaiveld of waterbodem uitgerekend. Opbrengstschattingen kunnen tot desgewenst vijftig meter onder het maaiveld of de waterbodem worden gemaakt. Er kan in principe tot deze en zelfs grotere dieptes worden gebaggerd, maar in verband met stabiliteit zou hiervoor ook het areaal van de zandwinput moeten worden vergroot.

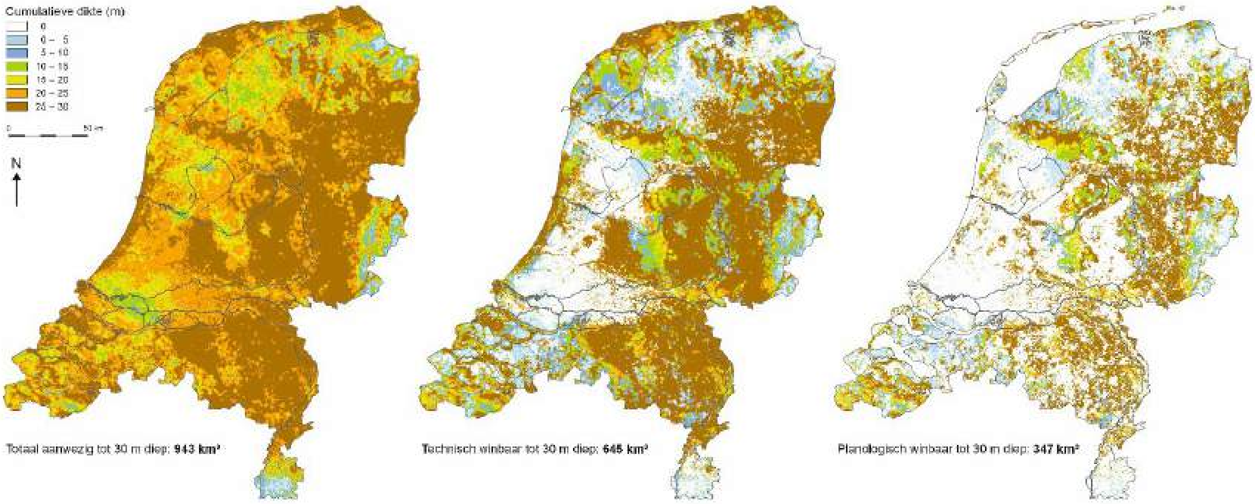
Voor de technische winbaarheid is gerekend met een deklaagcriterium van 5 meter: zand en grind bedekt door een toplaag van meer dan 5 meter klei en/of veen worden als niet winbaar beschouwd. Er is een stoorlaagcriterium gehanteerd van 2 meter, wat betekent dat als inschakelingen van klei en veen van boven naar beneden een cumulatieve dikte hebben bereikt van 2 meter, het zand en grind daaronder als niet meer winbaar worden beschouwd. Bij deze grenzen is niet zozeer sprake van een technische maar een economische limiet: als ze zijn bereikt (of worden benaderd) zal er elders in Nederland makkelijker en dus goedkoper gewonnen kunnen worden. Voor details over de methode wordt verwezen naar bijlage 2 (Van der Meulen et al., 2005).

Tabel 2. Planologische winbaarheid in relatie tot de hoofdgroepen en categorieën van het CBS Bestand Bodemgebruik 2020 (NBBG2020.PB.V2.VLP). CBS, 2020. Bestand Bodemgebruik 2020 (NBBG2020), V2, Bijsluiter 2.

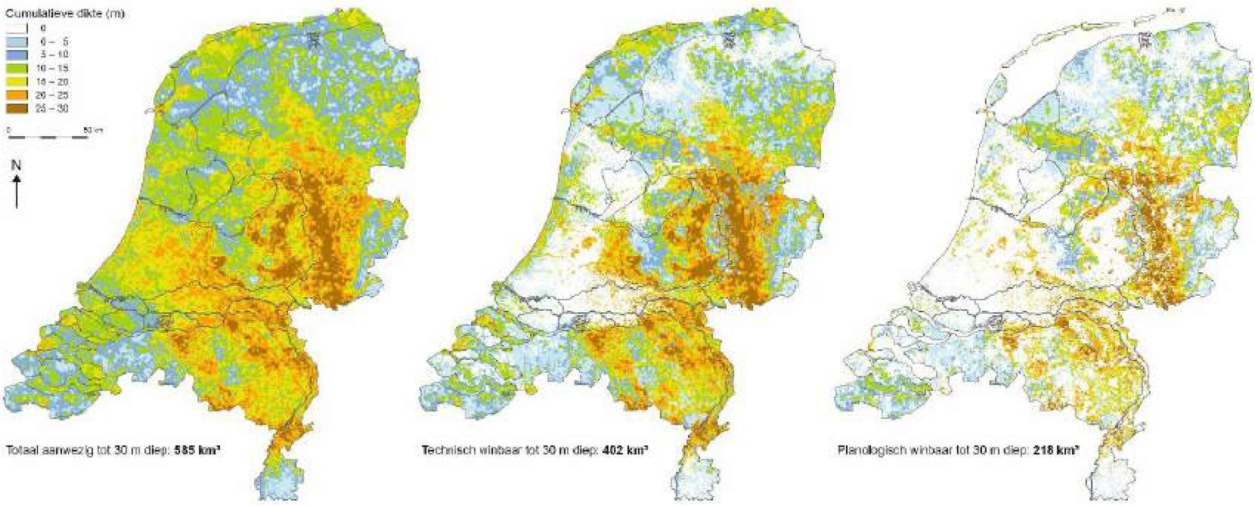
Hoofdgroep	Planologisch niet winbaar	Planologisch winbaar
1 – Verkeersterrein	Alle categorieën	
2 – Bebouwd terrein	Alle categorieën	
3 – Semi-bebouwd terrein	Alle categorieën	
4 – Recreatieterrein	Alle categorieën	
5 – Agrarisch terrein	Glastuinbouw (50)	Overig agrarisch terrein (51), Akker meerjarige teelt (52), Agrarisch grasland (53)
6 – Bos en open natuurlijk terrein	Alle categorieën	
7 – Binnenwater	Afgesloten zeearm (71), Rijn & Maas (72), Spaarbekken (74), Recreatief binnenwater (75), Binnenwater voor delfstofwinning (76), Vloei- en/of slibveld (77), Overig binnenwater (78)	IJsselmeer & Markermeer (70), Randmeer (73)
8 – Buitenwater	Waddenzee, Eems & Dollard (80), Oosterschelde (83)	Westerschelde (82)
9 – Buitenland	NVT	NVT

Voor het bepalen van de planologische winbaarheid op land is gebruik gemaakt van het CBS-Bestand Bodemgebruik (tabel 2). Uitgesloten voor winning zijn alle vormen van bebouwd terrein, natuurgebieden (met uitzondering van het IJsselmeer, Markermeer, Randmeren en de Westerschelde), binnenwateren (behoudens de uitgezonderde natte natuurgebieden) en de grote rivieren (zomerbed).

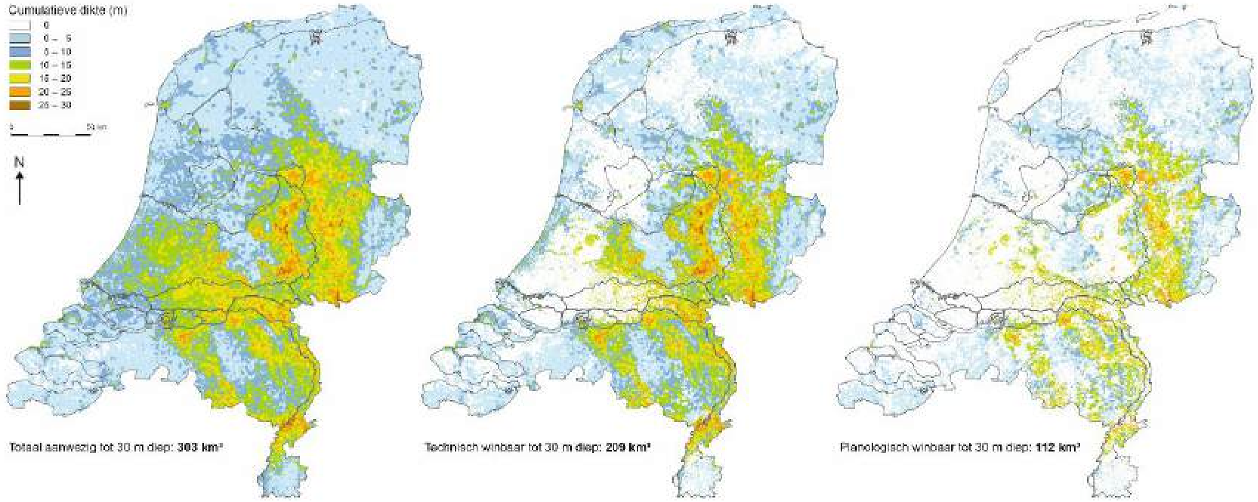
Figuren 1 t/m 4 tonen het voorkomen van alle zand en grind, en vervolgens steeds grovere subcategorieën waaruit industriezand en grind kunnen worden geproduceerd, tot 30 m onder maaiveld of waterbodem. In verband met de discrepantie tussen de industrie- en geologische definities van grind, is de verbreiding van grind figuur 4 niet gebaseerd op basis van korrelgrootte van monsters maar bepaald binnen het verbreidingsgebied van grof maasgrind (zie bijlage 2).



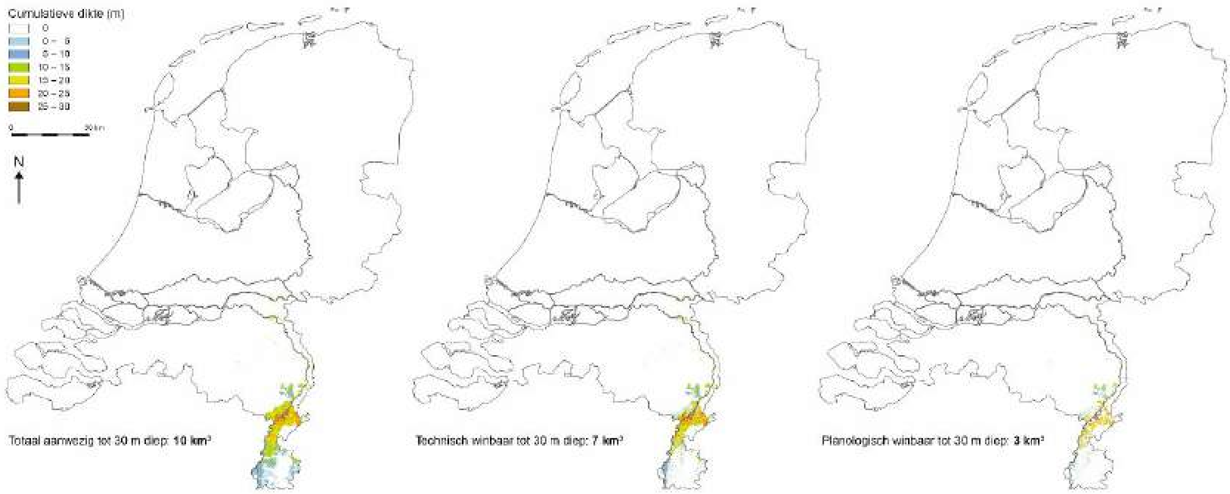
Figuur 1. De aanwezigheid, technische winbaarheid en planologische winbaarheid van zand en grind in Nederland tot een diepte van 30 m onder maaiveld.



Figuur 2. De aanwezigheid, technische winbaarheid en planologische winbaarheid van zand en grind tot een diepte van 30 m onder maaiveld waaruit industriezand en grind kunnen worden geproduceerd (kalkzandsteenzand, metselzand 0-1, betonzand 0-4 en grind).



Figuur 3. De aanwezigheid, technische winbaarheid en planologische winbaarheid van zand en grind tot een diepte van 30 m onder maaiveld waaruit grof industriezand en grind kunnen worden geproduceerd (betonzand 0-4 en grind).



Figuur 4. De aanwezigheid, technische winbaarheid en planologische winbaarheid van grind tot een diepte van 30 m onder maaiveld.

Integratie van de dikte van totaal aanwezige, technisch winbare en planologisch winbare voorraden over oppervlak levert de volumes op die in km³ zijn weergegeven onder elke kaart en worden samengevat in 3.4 / Tabel 4. Een km³ correspondeert grofweg met 17 keer de jaarlijkse huidige productie van granulaten uit Nederlandse bodem en 11 keer het huidige totaalverbruik (inclusief geïmporteerde en secundaire granulaten).

In de gecombineerde kaartbeelden komt de in de inleiding genoemde trend naar voren dat de korrelgrootte ruwweg van zuidoost naar noordwest afneemt. Verder is een deklaag van klei en veen in de kustprovincies op twee manieren relevant. De dikte ervan komt in mindering op de totale hoeveelheden aanwezig zand en grind en is bepalend voor de winbaarheid van het onderliggende zand. Beide trends leiden tot een sterke regionale variatie in de mogelijkheden om de grovere granulaten te winnen. Voor een indruk hiervan worden in tabel 3 de aandelen van planologisch winbare hoeveelheden van de twee categorieën zand weergegeven. Twee derde van de grofste categorie komt voor in Overijssel, Gelderland en Noord-Brabant.

Tabel 3. De planologisch winbare hoeveelheden industriezand en -grind per provincie exclusief Rijkswateren en voor de Rijkswateren tot een diepte van 30 m. In de aandelen per provincies zijn de Rijksbinnenwateren niet meegenomen.

Provincie	Zand 0-1 en grover (km³)	Aandeel (%)	Zand 0-4 en grover (km³)	Aandeel (%)
Groningen	9	5	2	2
Friesland	13	6	4	3
Drenthe	19	9	7	6
Overijssel	36	18	23	21
Flevoland	10	5	5	4
Gelderland	42	21	27	25
Utrecht	6	3	4	4
Noord-Holland	6	3	2	2
Zuid-Holland	4	2	2	2
Zeeland	6	3	1	1
Noord-Brabant	37	18	21	20
Limburg	15	7	10	9
Rijksbinnenwateren	15		5	
Totaal	218		112	

3.2 Reserveringszone zandwinning Noordzee

Tot op heden is er op het Nederlands Continentaal Plat (NCP) een reserveringszone voor zandwinning gedefinieerd van de doorgaande -20m dieptelijn en tot 12 nautische mijl uit de kust. De -20m dieptelijn geldt als zeewaartse begrenzing van het kustfundament, waaraan geen zand mag worden onttrokken. In de Ontwerp Partiële Herziening Programma Noordzee 2022 – 2027 wordt de reserveringszone uitgebreid tot 14 nautische mijl uit de kust.

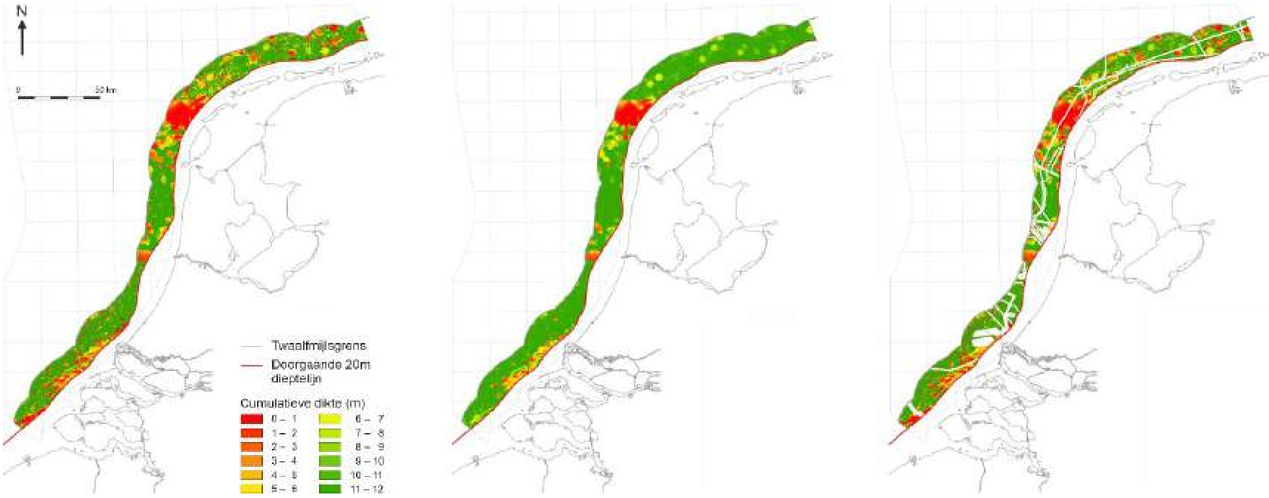
Voor het voorkomen van zand in de huidige reserveringszone maken Deltares en de GDN het Delfstoffeninformatiesysteem DIS. In het DIS wordt zand geïnventariseerd tot een diepte van 12 meter onder het zeebodemoppervlak, wat te maken heeft met de diepte van hiervoor beschikbare boorgegevens. Bij een windiepte die op zee de laatste jaren is opgelopen tot ongeveer 8 meter is deze inventarisatiediepte voldoende, maar voor grote projecten zoals de Maasvlakte II is er tot 20 meter diep gewonnen.

Op de Noordzee wordt tot dusver alleen ophoog- en suppletiezand gewonnen. Het DIS brengt echter ook het aandeel grover zand in beeld, met het idee dat zeezand zou kunnen worden gebruikt voor de industriezandproductie.

Voor winbaarheid wordt er voor het DIS gerekend met verschillende opties voor stoorlagen en bijmengingen, op een manier die vergelijkbaar is met het land. Verder wordt er onderscheid gemaakt tussen zogenaamde korte- en langetermijnvoorraden. Bij het bepalen van kortetermijnvoorraden wordt rekening gehouden met gebruiksbeperkingen (vaarwegen, energie- en telecominfrastructuur, etc.). Deze worden geacht tijdelijk te zijn en worden voor de langetermijnvoorraden buiten beschouwing gelaten. Lange- en kortetermijnvoorraden komen daarmee respectievelijk overeen met de technisch en planologisch winbare voorraden op land.

Omdat het DIS al als basis wordt gebruikt voor beleid worden de gegevens ongewijzigd overgenomen. De totaal beschikbare hoeveel zand die in de reserveringszone is geïnventariseerd bedraagt 54 km³, waarvan 46 km³ technisch winbaar en 36 km³ planologisch. Op dit moment wordt er geen industriezand uit zeezand geproduceerd, daarom wordt van grovere subcategorieën in voorliggend rapport geen opgave gedaan. Voor de uitbreiding van de reserveringszone zijn op dit moment geen (boor)gegevens en modellen beschikbaar op basis waarvan kan worden gekwantificeerd wat deze toevoegt aan de geïnventariseerde zandvoorraad.

Deze eeuw is in de reserveringszone per jaar gemiddeld zo'n 50 miljoen m³ zand gewonnen voor ophogingen, landaanwinningen en suppleties, inclusief megaprojecten zoals de Tweede Maasvlakte, de zandmotor en de versterking van de Hondsbossche en Pettemer Zeewering. Ten opzichte hiervan is de hoeveelheid zand in de territoriale wateren zeer ruim, ook als bedacht wordt dat besloten zou kunnen worden om dieper te winnen of uit te wijken naar het NCP buiten de reserveringszone.



Figuur 5. De aanwezigheid, technische winbaarheid en planologische winbaarheid van zand in de kustzone tot een diepte van 12 m onder de zeebodem. Planologische winbaarheid is gelijk aan de korte-termijn winbaarheid in de DIS-rapportages. De hier getoonde kaartbeelden zijn van DIS 2018. Nadien zijn er voor deelgebieden verbeteringen aangebracht in de geologische modellen; resultaten hiervan zijn niet in de totaalcijfers verwerkt. Voor toekomstige gegevens, inclusief aggregatie van de verschillende deelprojecten, wordt verwezen naar het lopende DIS-project.

3.3 NCP buiten de reserveringszone

Voor een ruwe inschatting van de voorraden aan zand op de Noordzee buiten de (huidige) reserveringszone voor zandwinning is gebruik gemaakt van de GDN Oppervlaktesedimentkaart. Van het hierop aangegeven sediment wordt bij gebrek aan betere informatie aangenomen dat het tot (minstens) twee meter onder de zeebodem voorkomt – de hieronder gegeven volumina zijn het oppervlak van zandvoorkomens vermenigvuldigd met twee meter. Dit correspondeert met de minimum windiepte op zee.

Voor een systematische inventarisatie van zand op grotere diepten ontbreken de gegevens, behalve waar er windparken worden aangelegd (die op hun beurt vervolgens beperkingen inhouden voor zandwinning). Er kan geen dek- of stoorlaaganalyse worden uitgevoerd, waarmee het onderscheid tussen beschikbaarheid en technische winbaarheid wegvalt.

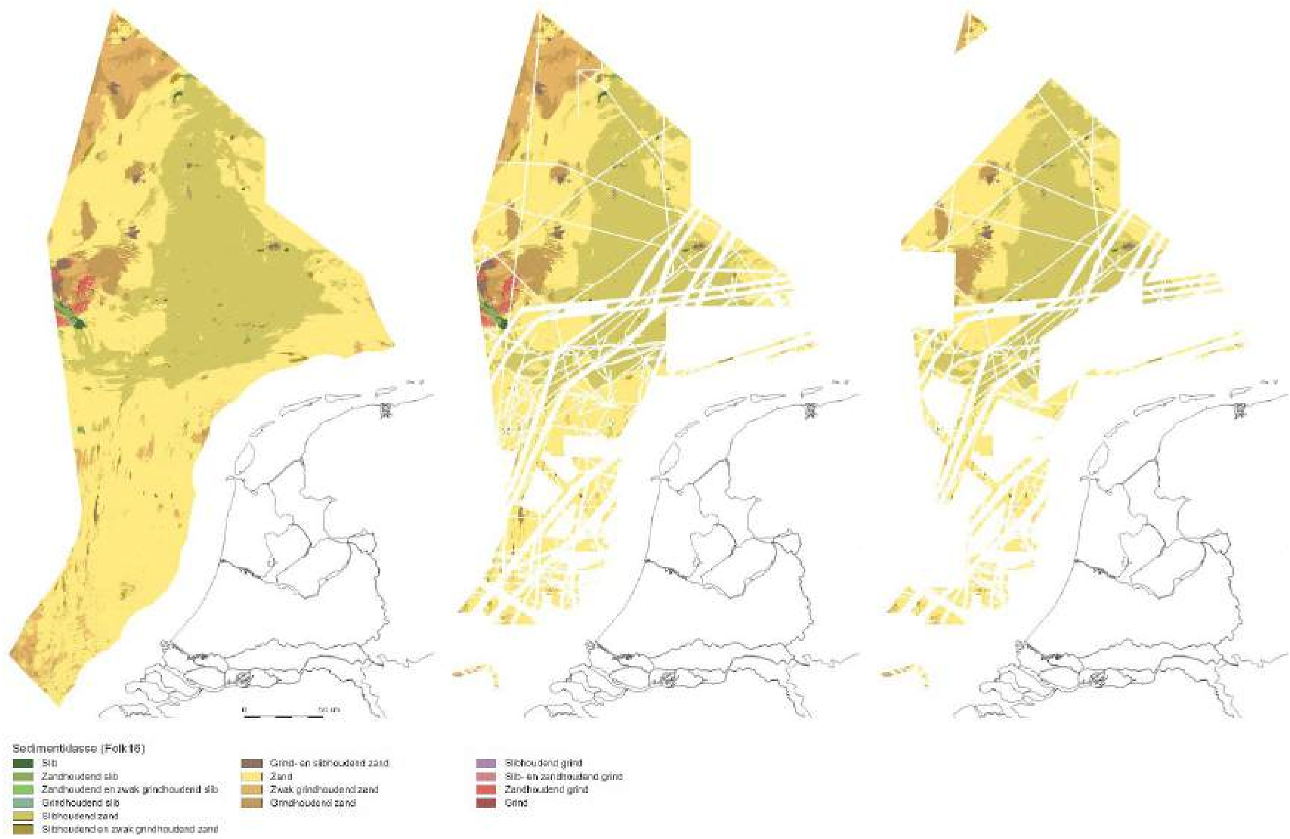
Gebieden waar slib (slib, zandhoudend slib, zandhoudend en zwak grindhoudend slib, grindhoudend slib), slibhoudend zand of slibhoudend en zwak grindhoudend zand

voorkomen zijn uitgesloten. Deze afzettingen zijn hetzij te fijnkorrelig om te gebruiken als grondstof, of met het zuigen zou teveel slib in de waterkolom worden gebracht.
Voor planologische winbaarheid zijn de volgende gebieden uitgesloten:

- Scheepvaartroutes Rotterdam, IJmuiden en ten noorden van de Wadden;
- Windparken met een buffer van 500 m;
- Kabels & leidingen een buffer van 500 m, incl. toekomstige formeel vastgelegde tracés;
- Ankergebieden en gebieden met hoge concentraties ankers;
- Verdiepte loswallen;
- Natura 2000-gebieden met een buffer van 900 m.

Van al het sediment wordt aangenomen dat het als ophoog- of suppletiezand kan worden gewonnen. Er kan weliswaar onderscheid worden gemaakt tussen zand en grovere sedimenten, maar niet op zo'n manier dat er industriezand- en grindopbrengsten uit kunnen worden berekend. Grindvoorkomens kunnen een waardevol hard substraat vormen voor bodemleven, de meeste vallen dan ook binnen natuurgebieden.

Bij een windiepte van 2 m, leveren de uitsluitingen een totale hoeveelheid zand op van 66 km³, waarvan 19 km³ valt binnen fysieke uitsluitingsgebieden en 11 km³ als daarvan de Natura2000-gebieden worden afgetrokken. Gezien de geringe inventarisatiediepte gaat het om een forse onderschatting van de werkelijk aanwezige voorraden.



Figuur 6. Oppervlaktesedimentkaart van de Noordzee buiten de reserveringszone voor zandwinning en twee categorieën uitsluitingscriteria.

3.4 Samenvatting beschikbare volumes

Tabel 4. Voorraden alle zand en grind (waaruit ophoogzand, kalkzandsteenzand, metselzand, betonzand en grind kunnen worden geproduceerd)

Gebied	Tot diepte (m)	Beschikbaar (km^3)	Technisch winbaar (km^3)	Planologisch winbaar (km^3)
NL excl. Noordzee	30	943	645	347
Territoriale wateren	12	54	46	36
Noordzee overig	2	66	66	19 / 11

Tabel 5. Opbrengst industriezand en grind (kalkzandsteenzand, metselzand, betonzand en grind)

Gebied	Tot diepte (m)	Beschikbaar (km^3)	Technisch winbaar (km^3)	Planologisch winbaar (km^3)
NL excl. Noordzee	30	585	402	218

Tabel 6. Opbrengst grof industriezand en grind (betonzand 0-4 en grind)

Gebied	Tot diepte (m)	Beschikbaar (km^3)	Technisch winbaar (km^3)	Planologisch winbaar (km^3)
NL excl. Noordzee	30	303	209	112

Tabel 7. Opbrengst grind.

NL excl. Noordzee	Tot diepte (m)	Beschikbaar (km^3)	Technisch winbaar (km^3)	Planologisch winbaar (km^3)
Land	30	10	7	3

4 Discussie en conclusies

4.1 Discussie

Ook al zijn de in voorliggende studie geïnventariseerde delfstofvolumes oplopend tot honderden km³ ontegenzeggelijk groot, is hun omvang pas werkelijk te duiden als ze worden vergeleken met behoefte en verbruik. Voor bijvoorbeeld olie, gas en kritieke grondstoffen wordt gewerkt met de R/P-ratio, de verhouding tussen reserves (vergunde voorraden) en jaarlijkse productie. Omdat deze grondstoffen wereldwijd worden verhandeld, wordt deze ratio mondiaal uitgerekend dan wel geschat. Voor oppervlaktedelfstoffen en bouwgrondstoffen—die weliswaar niet wereldwijd maar wel internationaal worden verhandeld—is dit niet mogelijk. Bij het ontbreken van internationale afspraken en standaarden zijn er geen opgaven van voorraden, reserves en productie in het publieke domein beschikbaar.

Om de omvang van de geïnventariseerde voorraden toch nader te kunnen duiden wordt gebruik gemaakt van de scenario's van de behoefte aan delfstoffen tot 2050 die Witteveen+Bos (2023) heeft gemaakt in opdracht van het Ministerie van I&W. Een vergelijking van de totaalbehoefte in tabellen 8 en 9 met de corresponderende totalen in tabellen 4 t/m 6 laat zien dat de technisch en planologisch winbare voorraden zand in Nederland een factor duizend keer groter zijn dan de geschatte jaarbehoeftes.

Tabel 8. De behoefte aan oppervlaktedelfstoffen in km³, behoedzaam scenario (Witteveen+Bos, 2023. Scenariostudie grondstoffenwinning. Ministerie van I&W: 59 pp., IV bijlagen).

Periode	Ophoogzand	Industriezand	Steenslag	Grind	Totaal
2023-2030	0,4	0,1	0,0	0,1	0,6
2030-2040	0,5	0,1	0,0	0,1	0,7
2040-2050	0,6	0,1	0,0	0,0	0,7
Totaal tot 2050	1,5	0,2	0,1	0,1	2,0

Tabel 9. De behoefte aan oppervlaktedelfstoffen in km³, dynamisch scenario (Witteveen+Bos, 2023. Scenariostudie grondstoffenwinning. Ministerie van I&W: 59 pp., IV bijlagen).

Periode	Ophoogzand	Industriezand	Steenslag	Grind	Totaal
2023-2030	0,5	0,1	0,0	0,1	0,6
2030-2040	0,7	0,1	0,0	0,1	0,9
2040-2050	0,8	0,1	0,0	0,1	1,0
Totaal tot 2050	1,9	0,3	0,1	0,2	2,5

Er moet wel worden bedacht dat de planologisch beschikbare hoeveelheden per definitie niet helemaal gewonnen zullen kunnen worden. Met zand (en grind) wordt immers een veel groter landoppervlak ingericht dan er nodig was voor de winning; het bebouwde gebied is vervolgens niet meer beschikbaar voor winning van delfstoffen. Gegevens om dit goed te kwantificeren ontbreken, maar in het geval van de Vinex-wijk Leidsche Rijn, met een oppervlak van 1100 ha, is er een zandwinplas van 90 ha gegraven voor het benodigde ophoogzand. Voor het beton van de gebouwen zelf zal een vergelijkbaar, waarschijnlijk kleiner areaal zijn afgegraven. Naar zeer ruwe schatting betekent dit dat er per ontgraven hectare een 5 à 10 keer zo groot gebied zal worden opgebouwd. Ook al neemt de planologische winbaarheid door bebouwing dus geleidelijk enigszins af, is er bij de beschikbare volumes zand in de ondergrond, ongeacht het type, echter geen sprake van geologische schaarste.

Daarentegen is de behoefte aan grove granulaten de komende eeuw—aannemend dat die ongeveer vier keer de hoeveelheid is die Witteveen+Bos tot 2050 heeft bepaald—slechts een factor tien groter dan de planologisch beschikbare voorraad grind. Grind mag in die zin dus geologisch schaars genoemd worden, wat overigens niet impliceert dat het op de internationale markt schaars is of hoeft te worden.

Hoeveel in Nederland gewonnen oppervlaktedelfstoffen er op de markt komen wordt niet bepaald door de geologische voorraden maar door hoeveel er mag worden gewonnen. Aanvragen voor ontgrondingsvergunningen worden in een breder ruimtelijke kader beoordeeld, waarin het belang van winning wordt gewogen tegen dat van andere vormen van ruimtegebruik. Het totale ruimtebeslag van delfstoffenwinning is overigens beperkt. In het publieke domein is weinig informatie beschikbaar, maar uit de Kraaijenbergse Plassen (400 ha) is bijvoorbeeld ongeveer 75 miljoen m^3 zand en grind gewonnen. In de ontginningsperiode ging het om een substantieel deel van de landelijke voorziening en het is nagenoeg gelijk aan de gemiddelde hoeveelheid industriezand die Witteveen+Bos tot 2050 per decennium als behoefte prognosticeert.

Behoudens in trajecten voor ontgrondingsvergunningen wordt er bij ruimtelijke plannen en afwegingen nauwelijks tot geen rekening gehouden met de aanwezigheid van oppervlaktedelfstoffen. Voor de meer schaarse materialen levert dit het risico dat ze worden gesteriliseerd[5] of verloren gaan. Uiterwaardverlagingen in het kader van het programma Ruimte voor de Rivier brachten bijvoorbeeld een discussie op gang over de aantasting van de 0.7 km^3 aan uiterwaardklei, die door de grofkeramische industrie als strategische voorraad werd beschouwd. Het omgekeerde gebeurde bij de Maaswerken: hier werd werk met werk gemaakt door grindwinning en rivierverruiming te combineren.

4.2 Conclusies

- De geïnventariseerde beschikbare voorraad zand in de Nederlandse ondergrond is een factor duizend keer groter dan de huidige jaarbehoefte.
- De geïnventariseerde beschikbare voorraad grind in de Nederlandse ondergrond is een factor tien keer groter dan de behoefte aan grove granulaten tot 2050. Grind kan hiermee als geologisch schaars in Nederland worden aangemerkt, overigens zonder te suggereren dat dit tot schaarste op de internationale markt leidt of hoeft te gaan leiden.
- Van de overige oppervlaktedelfstoffen, klei en zilverzand, zijn de geologische voorraden geringer maar is de vraag zodanig kleiner dat ze uit oogpunt van de voorziening niet als geologisch schaars hoeven te worden beschouwd.

[5] Sterilisatie betekent in dit verband het ontoegankelijk maken voor van delfstofvoorraden, in de regel door bebouwing.

Bijlage 1 – De Nederlandse bouwgrondstoffenvoor-ziening

Van der Meulen, M.J., Dijkstra, J.J., Koopmans, T.P.F., Pietersen, H.S., Stam, J., Maljers, D., 2025. Surface mineral resources. In: Geology of the Netherlands, Second Edition (eds. J.H. ten Veen, G.J. Vis, J. de Jager and Th.E. Wong): 679–699. Amsterdam, NL: Amsterdam University Press. doi:10.5117/9789463728362_ch18

18

Surface mineral resources

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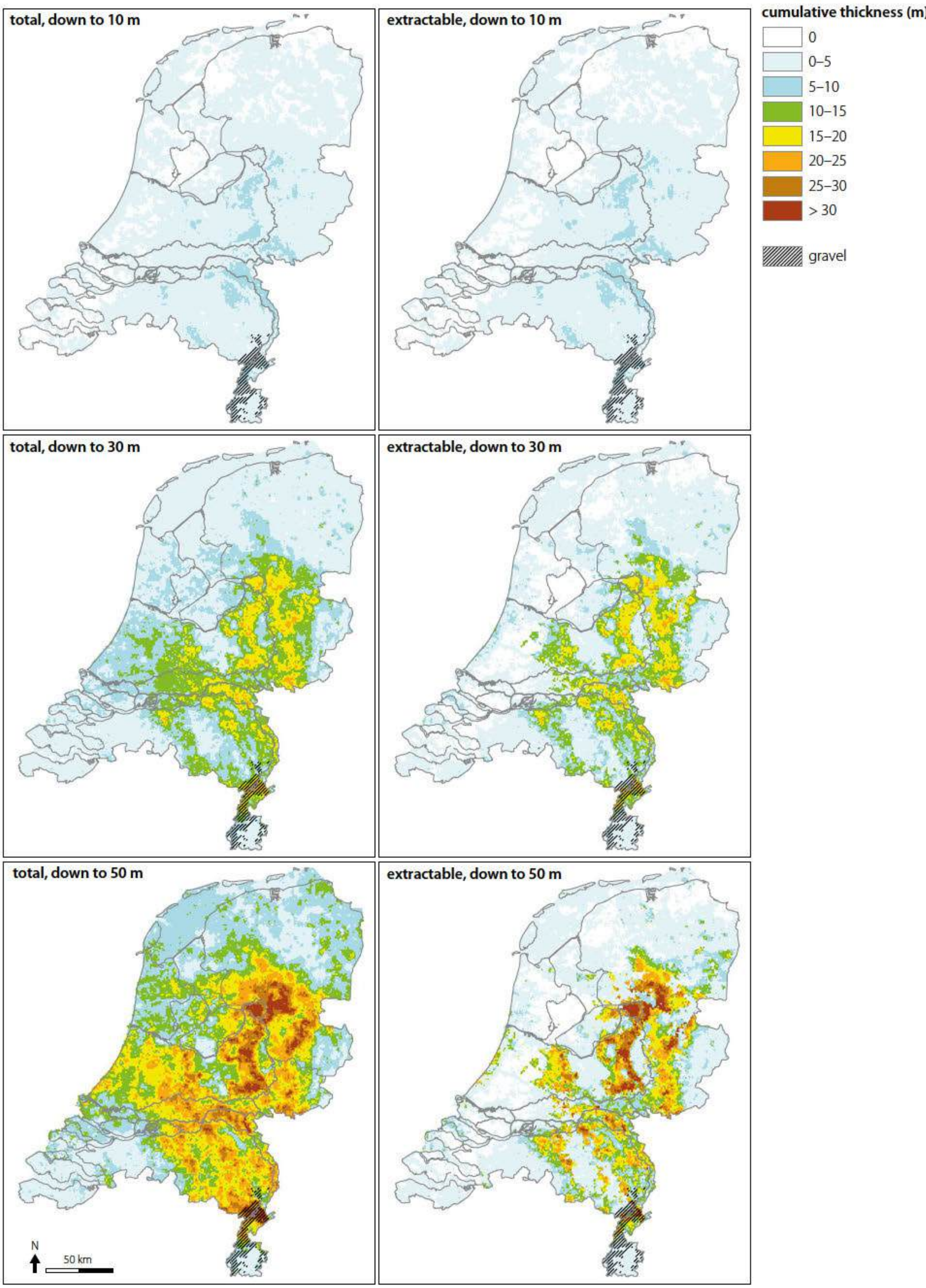
ABSTRACT

Dutch Quaternary and Neogene unconsolidated clastic deposits constitute major resources of aggregates and clay that are used in building and construction. Fine sand is available all over the country (including offshore), and is used mainly for filling, coastal nourishment and land reclamation. Coarse sand, which roughly occurs in the southeastern half of the country, is mainly used in concrete and masonry mortars. Gravel occurs in the southeasternmost part of the country, and is used in concrete and a variety of unbound applications. In addition to home-produced sand and gravel, the Netherlands uses significant amounts of imported and secondary aggregates. High-grade silica sand of Miocene age, occurring in the southeasternmost parts of the country, is used in several process industries. Clay is used for the production of structural ceramics (bricks and rooftiles), dyke building and maintenance, landfill covering and landscaping. Most ceramic clay is extracted from Holocene overbank deposits of the central/eastern Rhine-Meuse Delta. Clay for other applications is available all over the Holocene fluvial and coastal lowlands, except where peat is prevalent. Dutch carbonate resources include Cretaceous chalk in the southeasternmost part of the country, Triassic limestone and dolomite in the central-east, and Holocene shell deposits in the northern and southwestern tidal basins. Until recently, the chalk has been extracted to produce cement. The Triassic carbonates are grinded to powder and used in a variety of industrial and agricultural applications. The shells are used as drainage, paving and insulation material, or grinded for use in animal fodder.

<< Silica sand (*zilverzand*) of the Heksenberg Member in the De Groot quarry in Abdissenbosch (southeast Netherlands). Photo: Rudolf Bak.

DOI: 10.5117/9789463728362_ch18


total, down to 10 m
extractable, down to 10 m
total, down to 30 m
extractable, down to 30 m
total, down to 50 m
extractable, down to 50 m
cumulative thickness (m)
0
0–5
5–10
10–15
15–20
20–25
25–30
> 30
gravel
N
50 km

Introduction

Definitions

The production of geological resources in the Netherlands is governed by two laws. The Mining Act (Mijnbouwwet; Anonymous, 2002) applies to any use of the subsurface, including mining in the broadest sense, at depths greater than 100 m (or deeper than 500 m for geothermal energy). Over the past decades, this has mainly concerned the exploration and production of hydrocarbons and salt, but it has been extended to the storage of CO_2 (amendment of 2011) and geothermal energy (amendment of 2022). Classical underground mining has not taken place in the Netherlands since domestic coal production was terminated in 1975.

Surface mining, i.e. quarrying, excavating and dredging operations, is governed by the Environment and Planning Act (*Omgevingswet*; Anonymous, 2016). The legal distinction between surface and deep mining in Dutch policy recognizes the category of 'surface mineral resources' (*oppervlaktedelfstoffen*), the subject of the present chapter. It is based on depth of occurrence only and does not correspond to any common mineral categorization. Currently exploited Dutch surface mineral resources include aggregates, clay, silica sand and carbonates, all of which are industrial minerals, used mainly in construction. The only industrial mineral produced in the Netherlands that is not included in the surface mineral resource category is rock salt, which is treated in a separate chapter (Groenenberg et al., 2025, this volume).

Constitutionally, the Netherlands proper includes three municipalities in the Caribbean (the islands of Bonaire, Sint Eustatius and Saba), while the Kingdom of the Netherlands contains three additional constituent countries (the Caribbean islands of Aruba, Curaçao and Sint Maarten). Currently known mineral resources in the Caribbean parts of the Kingdom include building materials (in all six islands); gold (mined in Aruba from the early 1800s till the early 1900s); phosphate (mined in Aruba and Curaçao from the late 1800s till the early 1900s); copper (mined in Curaçao in the 1700s); and sulphur (mined in Saba from late 1800s till the early 1900s). The present chapter focusses on the Netherlands in Europe, including the Dutch sector of the North Sea and excludes the geologically unrelated Caribbean parts of the Kingdom.

Geological setting

The shallow subsurface of the Netherlands consists largely of unconsolidated Quaternary clastic deposits, which are discussed in Busschers et al. (2025, this volume). Their general physiographic setting is determined by uplifted sediment source areas in the catchments of the rivers Rhine, Meuse, Scheldt, and Eridanos (the Eocene-Pleistocene Baltic river system; Overeem et al., 2001), together with a few smaller rivers in the south and east of the country, as well as by the subsiding North Sea Basin in the west and north. Accordingly, Quaternary sediments generally grade from coarse-grained to fine-grained in a northwestward direction. Glaciations affected deposition, erosion and geomorphology repeatedly through the effects on sea level and vegetation, as well as directly by advancing ice sheets. Occurrences of Mesozoic and older solid rock at or near the surface are limited to the province of Limburg (southeast Netherlands) and the easternmost parts of the provinces of Gelderland and Overijssel (mid-east Netherlands), where they are related to the exhumation of the Ardennes massif towards the south and the Münsterland Cretaceous Basin towards the east, respectively. In both areas, Mesozoic carbonates are quarried for a variety of purposes or have been up until recently.

Aggregates

Introduction

Aggregate is the catch-all term for granular matter used in construction, either as such (e.g. as constructional fill, railway ballast, in slit drainage systems and for coastal nourishment) or with some binder (e.g. in concrete, asphalt, masonry mortars, etc.). In terms of mass and volume, they represent the most-used mineral resource worldwide (UNEP, 2019). The Netherlands is more or less self-sufficient in sand, resources of which are abundant (Fig. 18.1). However, as resources of gravel are comparatively limited and there is hardly any crushable rock at or near the surface, the Netherlands imports about 75% of these coarser aggregates.

Sometimes confusingly, the terms sand and gravel have different meanings in geology and in the extractive industry. In geology, they refer to either nominal grain-size fractions, or clastic sedimentary deposits having sand or gravel

← ***Figure 18.1.*** *Resources of coarse sand and gravel down to 10, 30 and 50 m below the surface, based on a nationwide 3D lithological model (Van der Meulen et al., 2005, 2007). The left panel shows the total cumulative resource thickness within the depth range indicated in the upper left corner. The right panels show cumulative extractable resource thickness. Aggregates are considered extractable according to criteria explained in the text. Grey hatching in the southeasternmost part of the country indicates the occurrence of gravel. The abundance of fine sand is more or less inversely proportional to that of coarse sand and gravel at depths >10 m in most of the country.*

as the dominant fraction. Regardless of the sediment classification scheme of choice, 2 mm is the limit between the sand and gravel fractions (cf. Wentworth, 1922; see Van der Meulen et al., 2005, 2007 and 2009; Jones et al., 2021 for a discussion). In industry, sand and gravel refer to specific types of aggregate products that are each, depending on the application, defined primarily by grain-size distribution. Processing of natural sand and gravel (classification, sieving) is generally required in order to meet specifications. Depending on the application, the lower grain size limit of gravel and corresponding crushed aggregates varies between 4 mm and 8 mm while the upper limit varies between 16 mm and 32 mm. Sand has a lower limit of 63 to 125 µm and an upper limit of 4 to 8 mm (Van der Meulen et al., 2005). In addition to grain size, aggregate specifications may include criteria for shape, physical or mineralogical properties of grains, or for bulk properties such as the friction angle.

For permitting and reporting purposes, the wide range of aggregate products is categorized into gravel and crushed rock, concreting and masonry sand, sand for sand-lime bricks, filling sand, sand for coastal nourishment, sand for land reclamation, and secondary aggregates. These aggregate types are discussed below in terms of applications, supplies and resources. Silica sand, which is used for its chemical composition in the process industry rather than for its physical properties in construction, does not belong to the aggregates family and is discussed separately.

Figure 18.2 shows Dutch aggregate consumption from 1980 to 2020. A clear correlation with the overall performance of the Dutch economy (expressed as GDP growth) reveals some of the main drivers behind minerals consumption and this is also evident in the statistics for individual commodities discussed below. Five major crises occurred in the time span represented in Figure 18.2. The global debt crisis of the early 1980s (Bakker, 1999) resulted in a marked decrease of aggregates consumption. The crisis was followed by almost two decades of more or less continuous growth in aggregate consumption, affected only by the mild European recession of 1991-1993 (e.g. Roy & Kemme, 2020). Aggregates consumption peaked in 2001, after which the Dutch economy came to a virtual standstill during the global recession of the early 2000s (Roy & Kemme, 2020) and aggregate consumption levels dropped accordingly. The Dutch economy was then hit by the Great Recession of 2007-2009 and the ensuing European Sovereign Debt Crisis (2009-2014; Kickert, 2012;

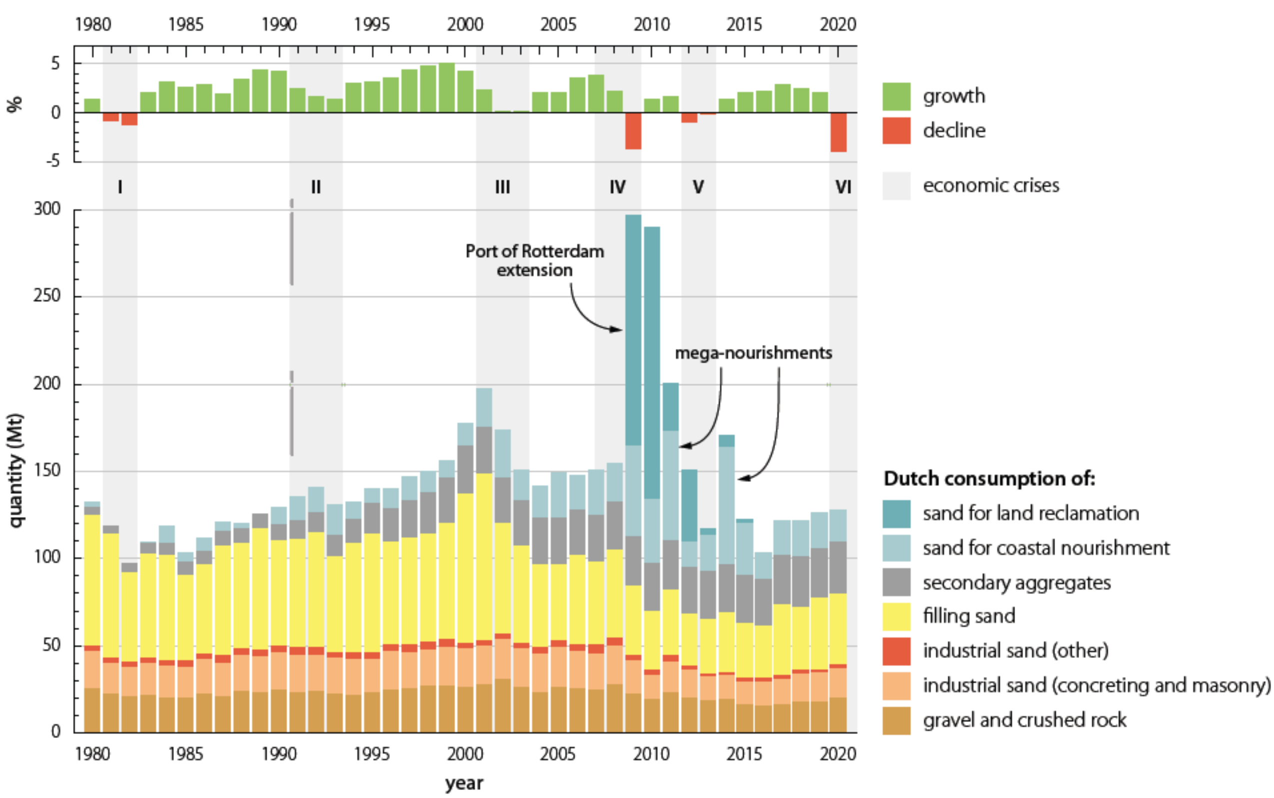


Figure 18.2. Lower panel: the consumption of aggregates in the Netherlands from 1980 to 2020. Upper panel: GDP-growth per annum, with an indication of economic crises: (I) global debt crisis, (II) European recession, (III) global recession, (IV) global financial crisis, (V) European sovereign debt crisis (VI) impacts of the Corona Pandemic. Production figures compiled from data provided by the Ministry of Infrastructure and the Environment (1980-2009), and MWH Global and H2H (2009-2020).

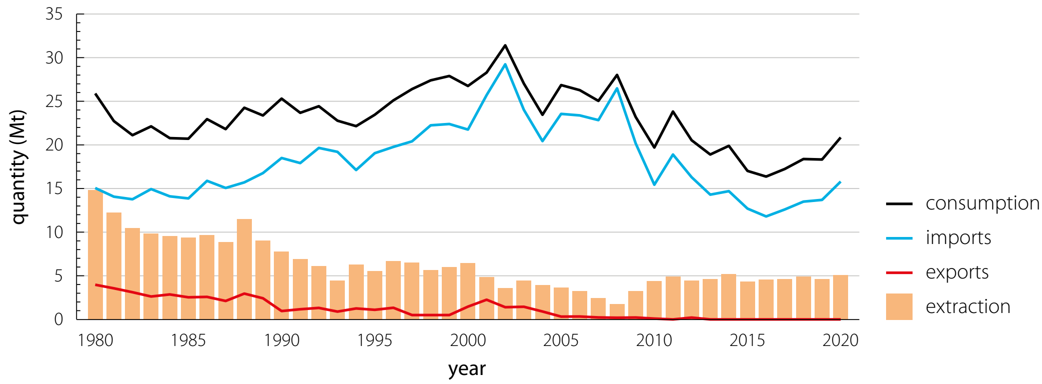


***Figure 18.3.** Dutch gravel and crushed rock supplies from 1980 to 2020. Sources: see Fig. 18.2.*

Ureche-Rangau & Burietz, 2013). These events, however, coincided with three major national projects discussed below which demanded vast amounts of marine aggregates. As a result the consumption of sand for land reclamation and coastal nourishment peaked at his time, while that of all other aggregates declined and stabilized below the levels of 1990-2010. The effects of the Corona Pandemic crisis on the economy and minerals consumption have yet to become evident.

Another clear trend is the increasing share of secondary aggregates, the use of which was promoted by national policy during the last decades of the previous century and which has led to a stable market for their use (discussed in detail in the section on secondary aggregates). In principle, all recyclable aggregates are reused, amounting to a significant substitution of primary aggregates.

Gravel and crushed rock

Applications and demand

The Dutch building industry uses around 19 Mt/yr of gravel and crushed rock, mainly in the production of concrete and asphalt, but also for unbound applications (e.g. railway construction and maintenance, and hydraulic engineering). About one fourth of the demand is met with home-produced gravel, almost all of which is extracted in the province of Limburg in the southeast of the country (Fig. 18.1). The long-term trends in demand are similar to those discussed for aggregates in general (Fig. 18.3). However, production steadily declined from 2000 to about 2008 in response to a government policy to gradually decrease production to the approximate level of provincial self-supply, in response to environmental concerns and because of local resistance against extraction (Van der Meulen, 2005). Production subsequently stabilized at the current level. Meanwhile, gravel imports rose accordingly (Van der Meulen et al., 2003, 2005), stabilising at the current level of about 5 Mt/yr, mainly from Germany, Belgium and the British sector of the North Sea. About 6 Mt/yr of crushed rock aggregates are imported from Belgium, Germany, Scotland, France and Norway.

All current Dutch gravel extraction permits are tied to *Maaswerken*, a project that combines river widening and aggregates extraction (Van der Meulen et al., 2006). They will expire in the foreseeable future, which means that home production of gravel will come to an end unless new permits are granted.

Resources

The main Dutch gravel resources are located in the province of Limburg (Fig. 18.1), where they have been deposited by the river Meuse from the Early Pleistocene onwards. As a result of syn-sedimentary uplift, they have been preserved in terraces that cover the flanks of the river valley. In the provinces of Gelderland, Utrecht, North-Brabant and Overijssel, i.e. roughly in the southeastern half of the country, gravel occurs as admixtures and intercalations in coarse Pleistocene sands, where they constitute by-products of concreting and masonry sand production (<1 Mt/yr). There are some isolated, relatively minor surficial occurrences of gravel and gravely sand in the Dutch sector of the North Sea. The largest of these is located in the area of the Cleaver Bank (Fig. 18.4) and was formed as an end moraine during the last glaciation and subsequently marine-reworked. The estimated amount of gravel in place is a mere 30 Mt (Laban, 2002), resolved at the level of UNFC Prospective Projects class (UNECE, 2019).

Concreting and masonry sand (*beton- en metselzand*)

Applications and demand

Concreting and masonry sand refers to a range of industrially produced coarse sands. About 75% is used for concrete production and about 15% in masonry mortars. The remaining ~10% is used for a wide range of purposes such as the production of asphalt and bricks, and for unconsolidated applications such as drains and filters. Each of these

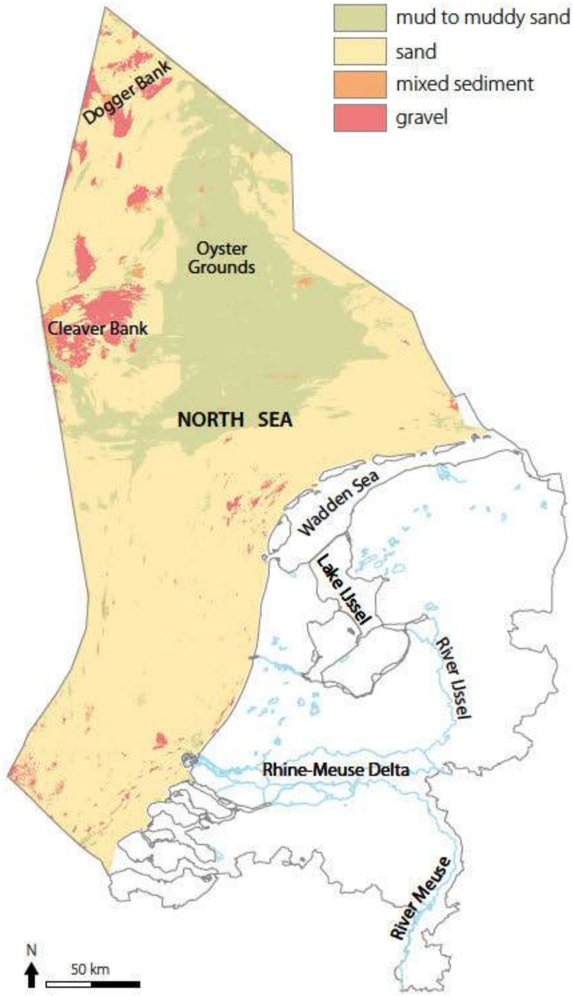


Figure 18.4. As the 3D lithological model used for Fig. 18.1 does not cover the Dutch offshore, a seabed sediment map for the Dutch sector of the North Sea Continental Shelf is provided as an indication of marine aggregate resources. Source: www.dinoloket.nl/en/subsurface-models/map (select seabed sediment).

applications has specific requirements for the grain-size distribution (Fig. 18.5) and, to some extent, for the grain shape of the aggregates. Producers have to sieve and blend natural aggregates in order to meet these requirements.

The demand for concreting and masonry sand shows more or less the same long-term trends as for aggregate in general: averaging at about 21 Mt/yr between 1980 and 2008, then dropping and stabilising at the current level of about 15 Mt/yr (Fig. 18.6). During the last 40 years sources of supply have shifted considerably. From the early 1980s until the late 1990s, a national policy was in place to approximately balance home production with demand by issuing sufficient permits to maintain the required supplies. However, due to the geological scarcity of sand suitable for concrete applications, the total production proved to be too little to meet the demand of Dutch concrete producers. Therefore, about 7 Mt/yr of coarse concreting and masonry sand were imported from Germany, while a similar amount of home-produced finer concreting and masonry sand was exported to Flanders (Belgium), which has limited coarse-sand resources.

Around 2000, the national government abandoned regulating the production of concreting and masonry sand (Van der Meulen, 2005). Home production decreased significantly and net imports rose to about 10 Mt/yr in 2003, remaining at such unprecedented high levels for 6 years. Only around 2015 has the balance between imports and exports been restored at about 5 Mt/yr, albeit under different economic circumstances and under a liberalized national permitting policy.

Resources

Concreting and masonry sand is mostly produced from Pleistocene fluvial deposits in the southern and eastern parts of the Netherlands (Kreftenheye, Urk, Beegden, Sterksel, Appelscha, Peize and Waalre formations; Busschers et al., 2025, this volume). These deposits protrude westward below the Rhine and Meuse riverplains and into the North Sea. However, since they are overlain by westward thickening, fine-grained Holocene flood and tidal basin deposits, and also display downstream fining, their exploitability and suitability for concreting applications in the coastal and North Sea areas is debatable (RWS,

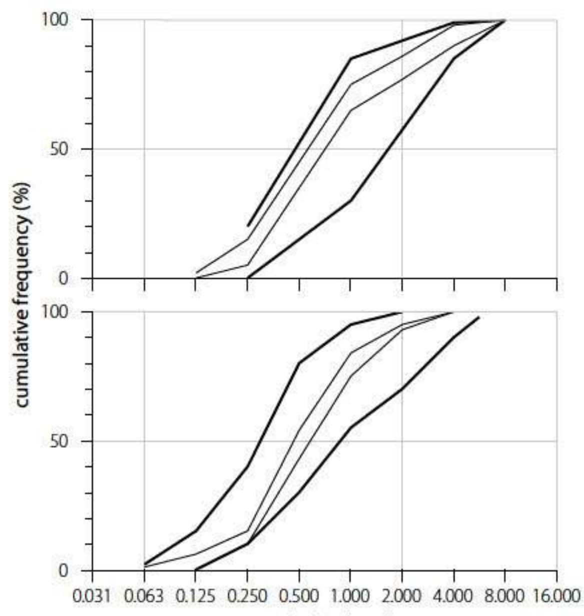


Figure 18.5. Grain-size distributions of the most important types of mortar sand (lower panel) and concrete sand (upper panel). Thick lines show the official minimum and maximum requirements (NEN, 1991, 1999); thin lines delimit the actual distributions on the market (RWS, 1998 and unpublished data).

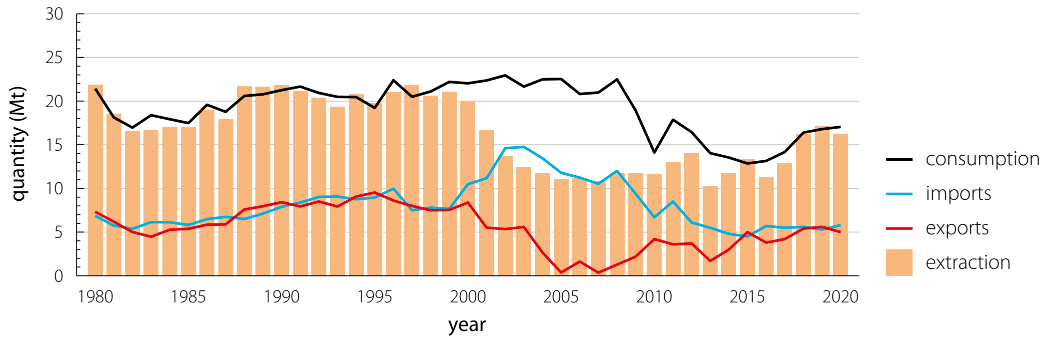


***Figure 18.6.** Dutch concreting and masonry sand supplies from 1980 to 2020. Sources: see Fig. 18.2.*

2004). Coarse-sand extraction sites exist throughout the eastern and southern Netherlands, but since much of the sand is shipped to its destination, most of it is extracted in the vicinity of major rivers.

Sand for sand-lime bricks (*kalkzandsteenzand*)

Sand-lime bricks are produced from a mixture of sand (~90%), lime (~7%) and water, which is moulded under mechanical pressure and then hardened under steam pressure and heating. They are mainly used for inside building walls. Sand for sand-lime bricks has a median grain size between 150 and 400 µm. Ten to 30% in the grain-size distribution has to be finer than 125 µm and an equal share coarser than 500 µm. Natural sands which meet these requirements are quite common in the Netherlands. The production is about 1.5 Mt/yr (Fig. 18.7).

Filling sand (*ophoogzand*)

Applications and demand

The western and northern parts of the Netherlands have a largely muddy or peaty subsurface that is prone to compaction and subsidence. Building in these areas therefore requires large amounts of filling sand as a foundation (De Jong & De Mulder, 1998). The current yearly demand is about 25 x 10^6 m^3, all of which is extracted in the country (Fig. 18.8).

The share of sand from the Dutch sector of the North Sea rose from approximately 10% in 1980 to about 50% in the early 2000s (Stolk & Seeger, 1999; Fig. 18.6). This increase is due to a policy of phasing out the extraction from the densely populated coastal provinces of North Holland and South Holland, and more recently from the province of North Brabant (southern Netherlands). After 2009 the relative share of marine sand for offshore use increased significantly, especially in connection with the extension of the Port of Rotterdam and the mega-nourishments discussed below.

Resources

In contrast to the other aggregates discussed above, filling sand has virtually no grain-size constraints and includes all sands which are unsuitable (i.e. too fine-grained) to be used for higher-value applications. Fine sand is available all over the Netherlands. The Dutch Holocene comprises a wide range of fine-grained sand bodies, deposited in sedimentary environments ranging from fluviatile to shallow marine. Resources in the North Sea are vast (Fig. 18.4).

In Limburg, hoggin (*stol*) is used for about 7% of the provincial filling-material requirement. It is extracted from fine-grained soils which developed on local Miocene-Pliocene fluviatile pebbly sands. The pebbly sand-loam mixture is relatively cohesive and is unsuitable for concreting and masonry sand production, but apt for use as filling or road-foundation material.

Sand for coastal nourishment (*suppletiezand*)

The current Dutch coastal defence programme, initiated in 1990, involves monitoring the coastline and coastal processes, and instigating measures at places where the coast is being eroded (Brand et al., 2021). Sustained coastal erosion is countered by the application of sand on

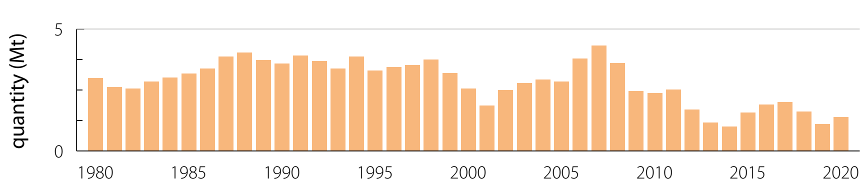


***Figure 18.7.** Production of sand for sand-lime bricks in the Netherlands from 1980 to 2020. Import and export figures are unavailable but are expected to be negligible. Sources: see Fig. 18.2.*

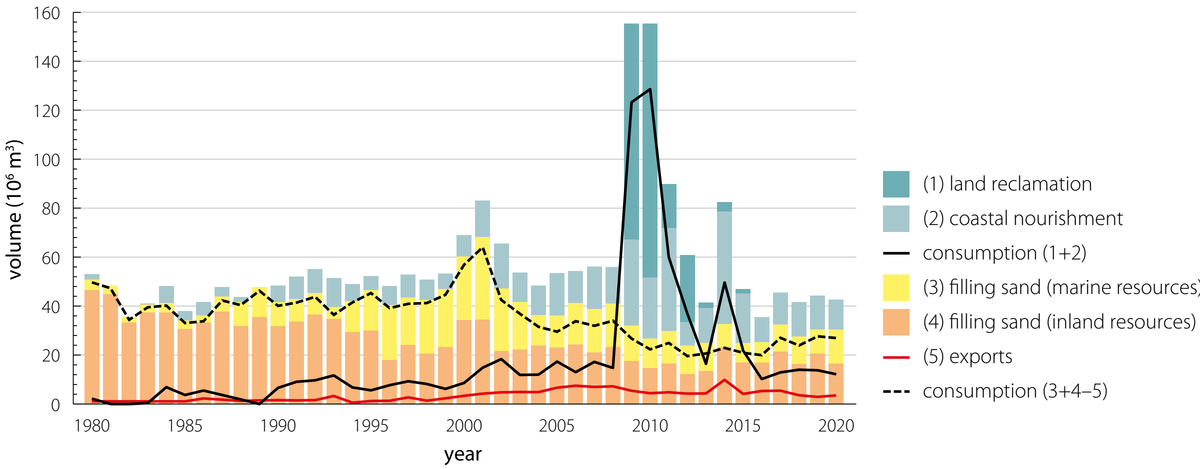


Figure 18.8. Dutch supplies of filling sand, sand for coastal nourishment and sand for land reclamation from 1980 to 2020. Amounts of these aggregates are usually given in volume rather than in weight units. Sources: see Fig. 18.2.

the beach or shoreface. The programme requires approximately 13 x 10^6 m^3 of sand per year (Fig. 18.8), which is extracted from the inner shelf as near as possible to the nourishment site. On top of that, one-off large coastal reinforcement and land reclamation projects may double or triple the use. Over the past decade, the Dutch coastal nourishment program was supplemented with two large individual coastal protection projects. In 2011, an innovative nourishment scheme was implemented that involved emplacing 21.5 x 10^6 m^3 of sand near The Hague (Stive et al., 2013). The resulting body of sand, the 'Sand Motor' (*Zandmotor*), reinforces a thin section of coastal dunes that was identified as a weaker zone in Dutch coastal defence policy. The sand is also intended to become eroded and dispersed along the coast via long-shore current sediment transport. Between 2013 and 2015, 30 million m^3 of sand were emplaced to reinforce the Hondsbossche and Pettemer sea defence, a large seawall erected in 1880 that has been used to protect a section of coastline without significant coastal dunes (Oost et al., 2015).

Sand for land reclamation (*landaanwinningszand*)

Between 1980 and 2009, the sand used to reclaim land from the sea was included in the sand for coastal nourishment statistics. However, when the Port of Rotterdam established its most recent seaward extension, *Maasvlakte II*, the 200 · 10^6 m^3 of sand it took to reclaim 20 km^2 of land in 2009 and 2010 (Fig. 18.8) was administered as a separate category. The port extension sits on the largest Dutch anthropogenic deposit created in a single project.

Secondary aggregates

Since the early 1990s, the substitution of primary by secondary aggregates has been stimulated by the Dutch national government through financial and regulatory instruments and, leading by example, by making use of secondary aggregates in national infrastructure projects. Since the mid-1990s, legislation and standards have been developed to enable the environmentally safe use of waste materials and industrial by-products in construction (e.g. VROM, 1995, 2007; Broers et al., 2002; Dijkstra et al., 2019). Reusing secondary aggregates reduces the consumption of the above primary aggregates in several applications, especially where filling is involved.

The share of secondary materials in the total provision has risen from ~7 Mt/yr (6%) in 1980 to ~32 Mt/yr (20%) in the early 2000s and stayed at approximately that level ever since (Fig. 18.2). Figure 18.9 is a breakdown of the secondary aggregate category in Figure 18.2 and considers the main types of secondary aggregates that are re-used in the Netherlands. Most of these materials, including granulated construction and demolition waste (CDW), steel slag and municipal solid waste incineration bottom ash (MWSI bottom ash), are currently used in unbound applications, replacing filling sand and coarse aggregate to an extent that should be accounted for in the total demand (see also Dijkstra et al., 2019). Typical applications include road foundations, landscaping, noise barriers, or ballast material in water works and coastal protection. Colliery spoil (not included in Fig. 18.9) is occasionally used for hydraulic engineering and as filling or paving material.

The strong rise in the use of secondary aggregates in the 1990s can mostly be attributed to CDW recycling. In 1985, the production of CDW was about 12 Mt/yr, of which 50% was landfilled and 50% was recycled (Hendriks & Pietersen, 2000; CLO, 2020). The steepest increase was coeval with the ban on landfilling of re-usable CDW in 1997 (VROM, 1997). The production of CDW stabilized in the years 2000-2014 at about 24 Mt/yr (CLO, 2020). Some other secondary aggregates in Figure 18.9 show a growth

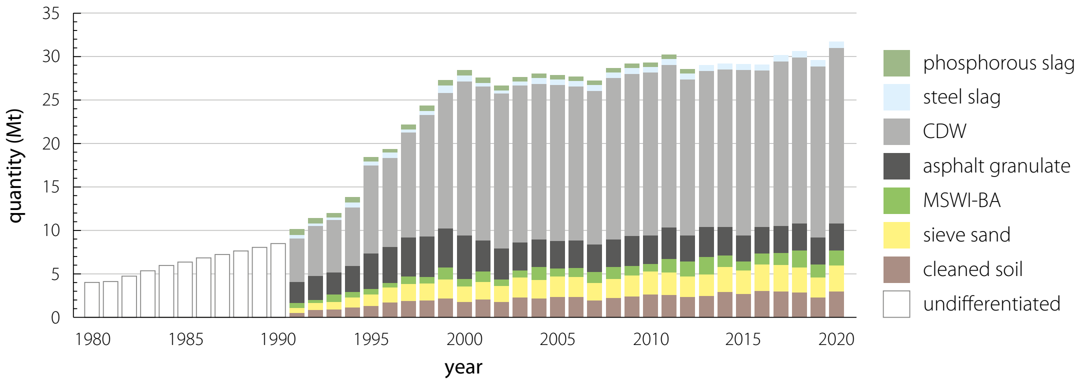


Figure 18.9. Main categories of secondary aggregates and their usage in the period 1980-2016 in the Netherlands. CDW = granulated construction and demolition waste. MSWI-BA = Municipal Solid Waste Incineration Bottom Ash, which is the main ash fraction originating from the combustion of household waste; sieve sand is the fine fraction from granulated construction and demolition waste; cleaned soil is thermally or wet-treated contaminated soil. Sources: Hendriks et al. (1999), RWS (2005, 2022), Bijleveld et al. (2015), Van Lieshout & Nusselder (2016), I&W (2017), 't Hoen (2017), CLO (2020), Tata Steel (2020).

as well. Most importantly, the use of MSWI bottom ash in infrastructural works doubled from 0.75 Mt in 1990-2000 to 1.5 Mt in 2010-2020 (RWS, 2005, 2022).

The use of secondary aggregates in bound applications such as concrete is relatively low. Replacement of concreting and masonry sand in bound applications is estimated to have been ~1 Mt/yr on a consumption of about 20 Mt/yr in the years 2001-2010 (about 5% replacement) and includes for instance sieve sand from construction and demolition waste and sand from asphalt granulate (MWH, 2012). Replacement of gravel and crushed stone by recycled concrete aggregate in new concrete amounted to a stable 0.5-0.7 Mt/yr in the years 2009-2016 (about 4% replacement, 't Hoen, 2017). In line with the Paris agreement (UN, 2016), the national government and the concrete sector expressed the ambition to achieve 100% circularity of the concrete production (*Betonakkoord*; Anonymous, 2018). Based on the ratio between the production volume of new concrete and the availability of recycled concrete aggregate, this could in theory result in a substitution of 15-20% of primary aggregate (Anonymous, 2018).

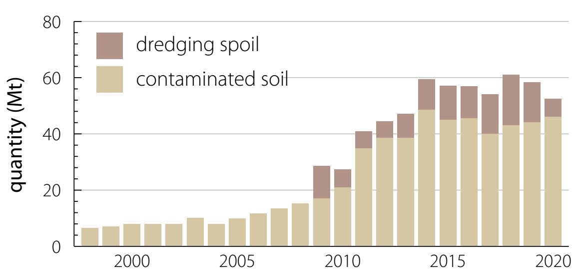


Figure 18.10. Amounts of contaminated soil and freshwater dredging spoil reused in the Netherlands. Source: RWS (2022).

Asphalt contains ~80-90 % m/m aggregate (sand, gravel, crushed rock; Bak et al., 2018). Asphalt granulate from infrastructural works is either recycled in unbound applications, replacing primary aggregate such as filling sand, or is recycled in new asphalt. MSWI fly ash is used as filler in asphalt, replacing sand. MSWI bottom ash has come to be treated and processed in such a way that its mineral fraction can substitute primary aggregate in concrete (e.g. Keulen, 2016).

Besides industrial wastes and by-products, increasing amounts of excavated contaminated soil and dredging spoil are partially replacing primary aggregates in unbound constructions (Fig. 18.10). Between 2010 and 2020, 91-95% of all excavated contaminated soil and 67-85% of freshwater dredging spoil was beneficially re-used in earthworks such as embankments and noise barriers (RWS, 2022), partially replacing filling sand. The remainder is too contaminated and is either treated, immobilized or landfilled. The (re-)use of freshwater dredging spoil peaked in 2018, when it was used in dyke maintenance (*Houtribdijk*, Lelystad) and in a large land reclamation project (*Marker Wadden*). However, it has sharply decreased following completion of these projects and also in response to the 'PFAS crisis', i.e. the widespread contamination of sediments with polyfluor-alkyl substances (PFAS) above the recognized safe limits (RWS, 2022).

Over the past decade, about 20% of the total re-use of contaminated soil and dredging spoil consists of backfilling sand and gravel extraction pits ('t Hoen, 2018). Although this practice can be viewed as the most literal replacement of primary aggregate by secondary materials, it cannot be attributed unambiguously to the substitution of primary aggregates in construction.

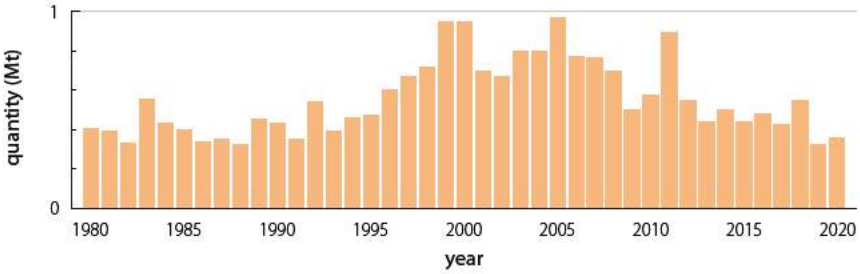


Figure 18.11. The production of silica sand in the Netherlands from 1980 to 2020. Sources: see Fig. 18.2.

Silica sand (*zilverzand*)

Applications and demand

Silica sand is a quartz resource employed in several industries (Van der Meulen et al., 2009). Various types of silica sand, with minimum SiO_2 percentages ranging from 97.0 to 99.8%, are used in the glass industry (~55%), the chemical industry (15%; the production of, e.g. water glass, zeolites and carborundum (SiC)), the ceramic industry (~20%) and foundries (~10%). Lower-grade silica sands are used when a white colour is desired for, e.g. masonry, the sand joints in pavements, or the production of sand-faced bricks. Table 18.1 shows the quality requirements for the main applications of silica sands in terms of quartz, iron, aluminium and titanium contents, and loss on ignition. Additional quality parameters, not shown in the table, include the grain-size distribution, and the chromium (Cr) and heavy-mineral contents.

Natural silica sands usually do not meet the industrial requirements and have to be upgraded. Impurities related to specific grain-size fractions such as clay are removed by washing or wet screening. Grain coatings of iron minerals such as limonite can be removed by attrition (scrubbing), or acid leaching (both cold and hot). Froth flotation and magnetic- or gravity separation methods are used to remove discrete contaminant minerals. The silica sands currently extracted in the Netherlands usually require only washing, or the combination of washing and attrition.

The production of silica sand was around 0.4 Mt/yr in the 1980s and has risen to around 0.8 Mt/yr in the early 2000s (Fig. 18.11). The rise was largely an increasing use of somewhat lesser-grade silica sands, which are more abundant. After that, the production of silica sand shows the economically driven trends shown in Figure 18.2 for aggregates. There are no accurate import and export figures. Exports to Germany are known to be significant and silica sand is imported from Belgium and Germany.

Resources

Currently exploited silica sands of the Miocene Groote Heide Formation (Munsterman et al., 2025, this volume) of South Limburg, near the town of Heerlen (Figs 18.12, 18.13), rank among the purest in Europe. The high quartz contents are the result of a combination of a quartz-rich source material, sorting in a coastal depositional environment and pedogenic processes (Van der Meulen et al., 2009). The silica sand is often intercalated with brown-coal layers, which may have acted as adsorption filters reducing the mineral content of percolating groundwater.

High-grade silica sand is used to produce silicon metal, which in its turn is listed as a critical raw material, i.e. a raw material of high economic importance with a high risk of supply disruption due to a dependency of imports from a very limited number of producing countries worldwide and lack of substitutes. The European Critical Raw Materials Act (EC, 2023) defines several types of actions

Table 18.1. Matrix of five categories of silica sand (1-5) and their applications in the structural ceramic industry (A), foundries (B), low-grade glass (C), fine ceramics (D), high-grade glass I, water glass, zeolites (F) and carborundum (SiC) (G). The quality per category is given in terms of minimum quartz (SiO_2) and maximum iron (Fe_2O_3), aluminium (Al_2O_3) and titanium (TiO_2) contents, as well as the maximum loss on ignition (LOI; %m/m). Modified from Feenstra & Mulder (2003).

		Applications							Chemical characterization				
		A	B	C	D	E	F	G	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	LOI
Categories	1					x	x	x	99.80	0.01	0.05	0.02	0.05
	2				x	x	x	x	99.70	0.02	0.08	0.03	0.10
	3				x	x	x		99.50	0.03	0.14	0.04	0.25
	4		x	x					99.0	0.1	0.2	0.1	0.5
	5	x	x						97.0	0.5	0.5–0.10	0.3	1.0

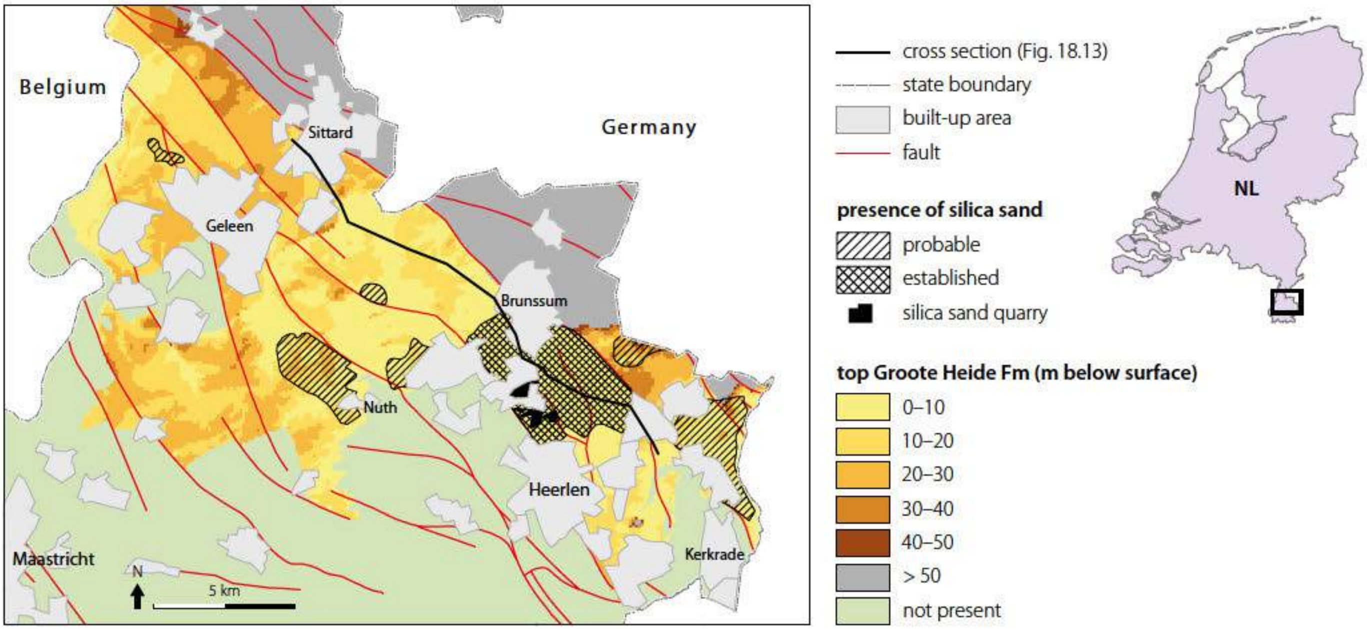


Figure 18.12. The distribution of silica sand in South Limburg. The top of the Groote Heide Formation is shown because silica sand in the area occurs in this stratigraphic unit (more detail in Fig. 18.13). Modified from Van der Meulen et al. (2009), reprinted with permission.

to secure supplies, one of which is to revive mining in Europe. This act will in its turn require the Dutch government to treat high-grade silica sand as a strategic resource and ensure some form of planning protection that is now not in place. Such policy would not only need to apply to the known, high-grade resources in the province of Limburg, but also to lower-grade sands that occur locally in the eastern and southern parts of the country (Van der Meulen et al., 2009).

Clay

Applications and demand

The structural ceramic industry uses an estimated amount of 1.5×10^6 m^3/yr of clay, mainly for the production of bricks and roof tiles (Fig. 18.14). Traditionally, bricks were the most important construction material in the Netherlands, but nowadays, they are mainly used for outer walls (Van der Meulen et al., 2007). Customer demands for certain colours or textures are important to the industry. These and other properties, such as behaviour during drying and firing, as well as the strength of the end product, are determined by the clay chemistry and mineralogy, and the sand and organic-matter contents (Van der Zwan, 1990; Van Wijck, 1997; Table 18.2). In order to obtain the desired clay mixtures, producers add sands or clays from other localities to their local stocks. Limited amounts of clay are imported for this purpose, mainly from Germany.

Clay (which in this case also includes loam) is also used for the building and maintenance of dykes, the covering of landfills, and landscaping. The material specifications for

Table 18.2. Approximate requirements for clay in the structural ceramic industry and for dyke maintenance (modified from Van der Zwan, 1990). Note that clay in the industrial definition may include fine-grained loam and silt, if they are sufficiently cohesive. Anonymous (2001) defined clay raw materials (in both applications) as having clay percentages between 17.5 and 35. Clays meeting this criterion are shown in Fig. 18.12.

Application	Share of grain-size fraction (% m/m)					C-org	$CaCO_3$
	Clay	< 10 µm	63–250 µm	> 250 µm	Sand	(% m/m)	(% m/m)
Roof tiles		50–57	< 20	< 40		< 3	< 25
Bricks		40–42	< 20	< 40		< 3	< 25
Extruded products		40–55	< 20	< 40		< 3	< 25
Dyke maintenance	18–40				< 40	< 3	

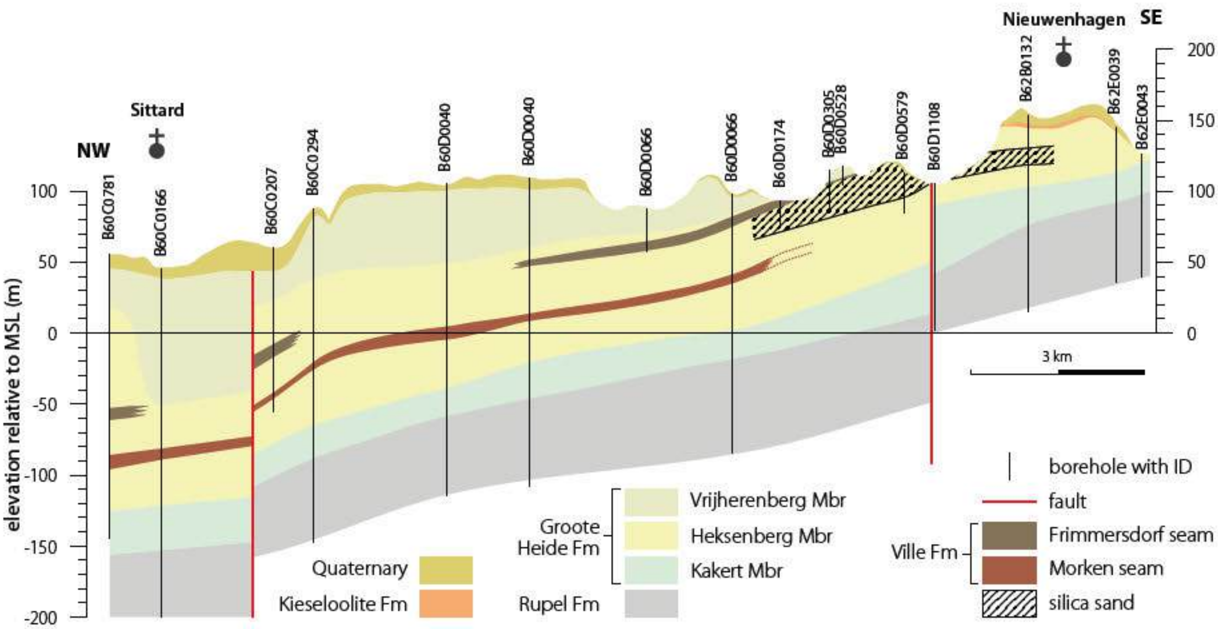


Figure 18.13. Profile through South Limburg (see Fig. 18.12 for profile line), showing the occurrence of silica sand in the Heksenberg Member of the Groote Heide Formation. Silica sand formation and the significance of the Frimmersdorf and Morken lignite seams are discussed in Van der Meulen et al. (2009), from which this figure is modified. Reprinted with permission.

such applications are related to the desired cohesiveness and impermeability. Up till the mid-1990s dyke maintenance required only relatively small amounts of clay, in the order of 0.5 to $1 \cdot 10^6\,m^3/yr$, but at that time, the demand rose spectacularly as a consequence of a major river-dyke upgrading programme, which was undertaken after two winters of exceptionally high waters and flood risk (Fig. 18.14). There is no differentiation in clay use statistics after 2002, but consumption peaks in that period are most probably in the 'other' category as well.

Resources

Quaternary overbank deposits of the rivers Meuse and Rhine and Holocene peri-marine clays in the coastal provinces provide the bulk of the Dutch clay resources (Fig. 18.15). Currently, the structural ceramic industry mainly uses the fluviatile clays, while the peri-marine clays are only used in the province of Groningen. Other exploited resources include Oligocene marine clays in the province of Gelderland, Quaternary brook deposits in the provinces of North Brabant, Gelderland and Overijssel, and Pleistocene eolian silt deposits in Limburg (loess).

Most of the ceramic clay extraction sites are located in the embanked floodplains of the central/eastern Rhine-Meuse Delta (RWS, 2001; Van der Meulen et al., 2007). Dutch rivers were progressively embanked from approximately 1000 AD onwards. Within the confinement of the dykes, the main river channel was initially free to migrate and able to deposit sand throughout the embanked floodplains (Middelkoop, 1997). From approximately 1850 AD

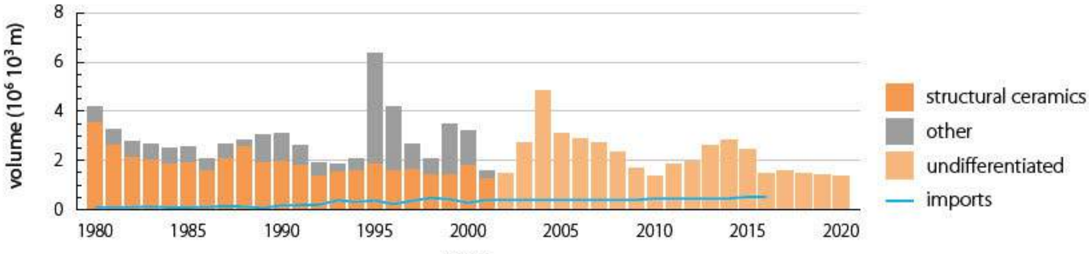


Figure 18.14. The extraction of clay for the structural ceramics industry and other applications (dyke building/maintenance, landscaping, lining of landfills) from 1980 to 2020. Reliable import figures for 2002-2020 are not available. Limited amounts of ceramic clay are imported, exports (not shown) are negligible. Amounts of clay are usually given in volume rather than in weight units. Sources: see Fig. 18.1.

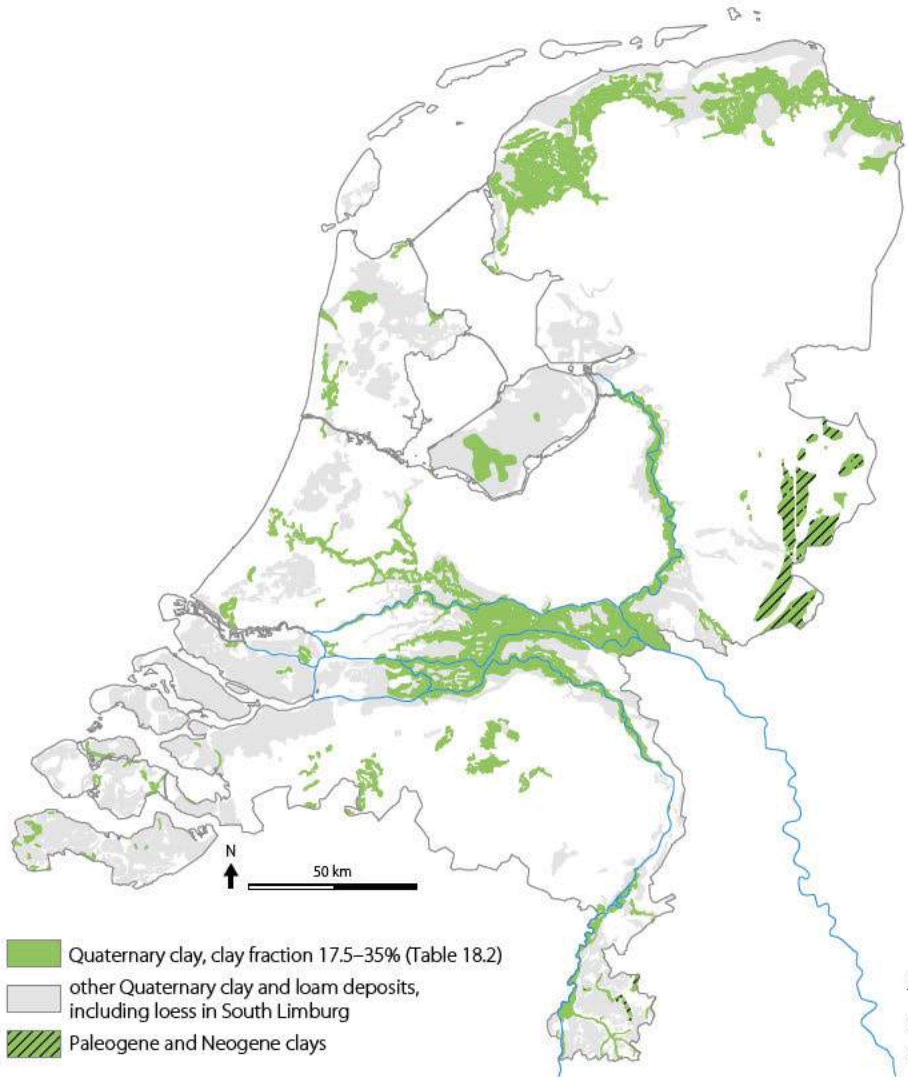


Figure 18.15. The distribution of superficial fine-grained deposits in the Netherlands.

onwards, however, the river channels were fixed by a combination of groyne construction, riverbed armouring and/or strengthening of natural levees. From that time, clay became the dominant overbank deposit in the embanked floodplains, while sand transport and sedimentation became limited to the river channel. These particular clay deposits have become the main resource for the structural ceramic industry and amount to about two-thirds in the total consumption. For dyke maintenance and the covering of landfills, locally extracted clay is used wherever possible.

Carbonates

Limestone and dolomite

Applications and demand

The only Dutch Portland cement production plant (ENCI), operational from 1926 until 2020, was located near the town of Maastricht in South Limburg. The plant operated a large quarry until 2018, where between 1.2-1.6 Mt/yrof chalk was extracted over the past decades (Fig. 18.16). The factory used various secondary materials such as blast furnace slag and coal fly ash for its pozzolanic properties, i.e. the ability to react with calcium hydroxide and form calcium silicates. After the permit to quarry chalk ended in 2018, the factory continued to produce cement until 2020 from clinker imported from Belgium.

About 0.3 Mt/yr of chalk, limestone and dolomite is quarried for the production of limestone powder in Limburg and eastern Gelderland (Fig. 18.16). Limestone powder is mainly used in agriculture (fertilizing, fodder), as a filler in ceramic products, paperware and asphalt, and for the desulphurisation of flue gases.

Chalk in Limburg has been used as dimension stone since the Roman era. Nowadays, only a minor amount of chalk is quarried for this purpose, mainly for reconstruction works. The Netherlands depends almost completely on imports of dimension stone, mainly from Belgium and Germany. Between 2000 and 2021, Dutch annual imports of dimension stone varied between 0.3 and 3.1 Mt (Statistics Netherlands).

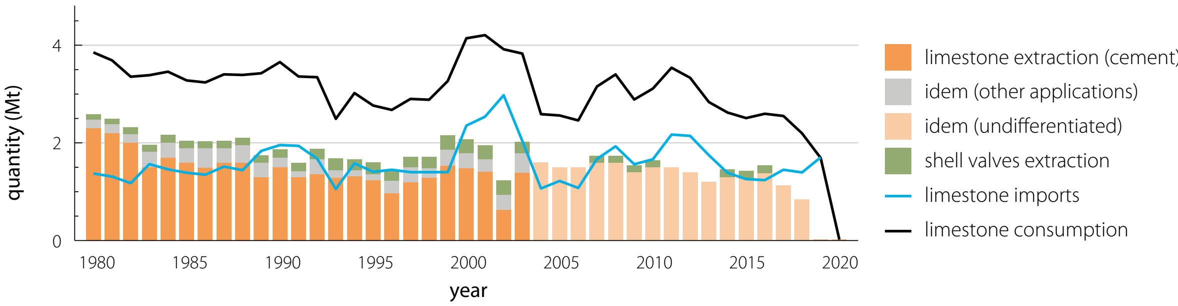


Figure 18.16. Dutch carbonate supplies 1980 to 2020 (excluding dimension stone). Exports (not shown) are negligible. Shell extraction data are incomplete. Sources: see Fig. 18.1.

Resources

Upper Cretaceous chalk deposits in Limburg form the most common pre-Cenozoic naturally exposed rocks in the Netherlands, and are the main carbonate resource (Fig. 18.17). The chalk was deposited as bioclastic carbonate muds, silts and sands in a shallow-marine basin that covered large portions of northwestern Europe during the Late Cretaceous and earliest Cenozoic (Zijlstra, 1994). The chalk has a very high $CaCO_3$ content (up to 99%); the only significant siliceous component being flint, which occurs in nodules or layers. The flint was used to make human tools as early as 6000 BP, and now is a by-product of limestone quarries, mainly used for road foundations, path pavements and hydraulic engineering.

Middle Triassic Muschelkalk carbonates quarried in Gelderland are an alternation of nodular limestone and dolomite, deposited in peri-marine environments. They have been quarried east of Winterswijk in the eastern Netherlands since 1933. The material is mainly used in road building and agriculture.

Shells

Mollusc shells are used in drains (~22%), path pavements (~20%), animal fodder (~16%), thermal and moisture insulation (~13%), and in several minor applications such as foundation material and the production of lime mortar (De Graaf et al., 2000). All applications except lime-mortar production make use of cockle shells (*Cerastoderma edule*), which endure intensive use and mechanical processing. When crushed, the combination of concentric growth increments and radial ribs results in approximately equidimensional fragments: a useful property for fodder production and path pavements.

Shell extraction was monitored from 1980 to 2002, but more recent statistics are sparse and less reliable. The current demand for shells is estimated at 150 x 10^3 m^3/yr. In the 1990s, extraction rose from about 180 to 290 x 10^3 m^3/yr (Fig. 18.16). About 70% of this amount was extracted from Holocene deposits of the Waddenzee and its inlets. The remaining 30% is mainly extracted from the Pleistocene of the Westerschelde estuary and its prodelta. For reasons of sustainability, the annually permitted volumes in these areas are limited to the estimated average yearly growth increments of the exploitable shell stocks (cf. Beukema & Cadée, 1999). An estimated amount of about 10 x 10^3 m^3/yr of cockle shells is obtained from seafood producers.

Some historically exploited resources

Peat that has accumulated in Quaternary paralic, fluviatile and lacustrine environments and has been exploited from Roman times up to the mid-20th century (Van Bergen & Koster, 2025, this volume). Historically, dried peat has mainly been used as fuel. In Roman to medieval times paralic peat has been extracted and burned to produce salt from the ashes. The current demand for dried peat in the production of horticultural compost etc., is almost completely met by imports, mainly from Germany. Between 2000 and 2021, Dutch annual imports of 'turf and derived products' varied between 1.8 and 2.9 Mt (Statistics Netherlands).

Bog ore. In the central and southeastern parts of the country, iron has been extracted from bog ore, iron (hydr-) oxide concretions, mainly from Pleistocene ice-pushed ridges in Gelderland (see Griffioen et al., 2025, this volume), and from siderite nodules (e.g. from the upper Carboniferous of southernmost Limburg; Laban et al., 1988; Joosten, 2004). Artisanal iron production started in prehistoric times and reached a high in medieval times. Since 1926, the Netherlands has been producing iron and steel from imported iron ore in its steelworks at the Port of IJmuiden located east of Amsterdam. Between 2000 and 2021, Dutch annual net imports of 'iron ore, iron, semi-products and scrap iron' varied between 2.7 and 8.1 Mt (Statistics Netherlands).

Till. Pleistocene subglacial tills in the northern and eastern parts of the country (Busschers et al., 2025, this volume) have been used for dyke building, in particular

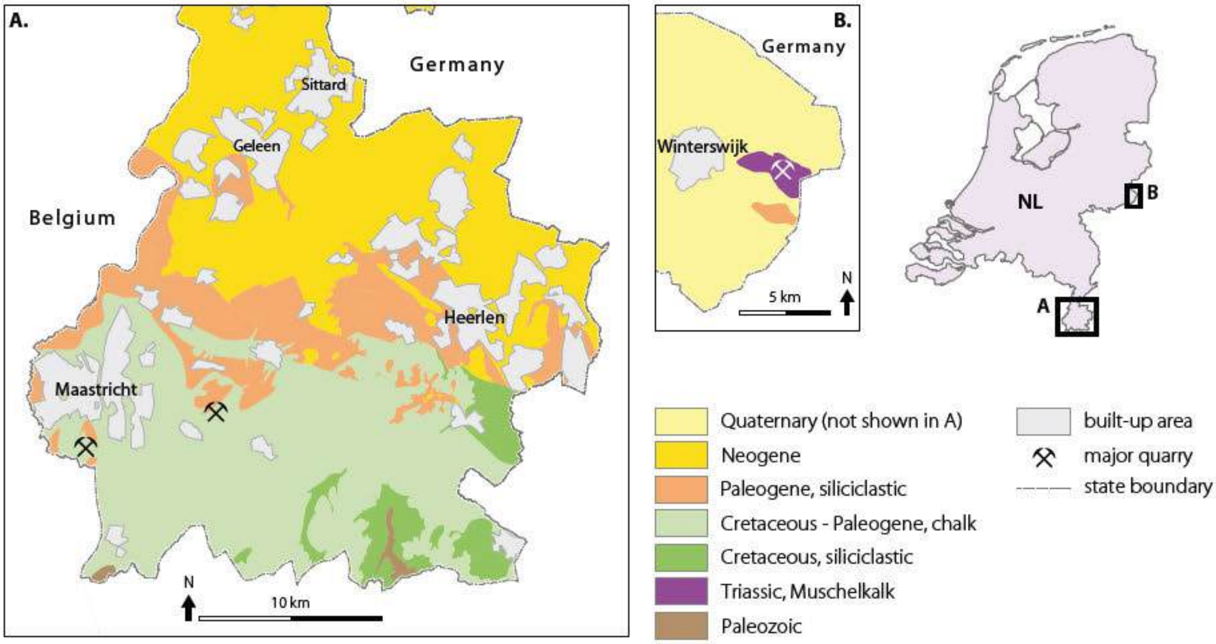


Figure 18.17. Carbonate resources: a) Pre-Quaternary sub-crop map of South Limburg showing Cretaceous to Paleogene chalk (source: RGD, 1989); b) Simplified geological map of Winterswijk and surroundings showing the occurrence of the Musschelkalk dolomite and limestone formation (source: TNO-GDN, 2023).

for the '*Afsluitdijk*', which separates Lake IJssel from the Wadden Sea (Fig. 18.4). Its construction, in 1927-1932, required 13.5×10^6 m³ of till and 23×10^6 m³ of sand.

Phosporite nodules. In eastern Gelderland and Overijssel, Oligocene phosphorite nodules occur in the shallow subsurface, either as a primary constituent of marine deposits, or reworked in Pleistocene moraines (Laban, 1988). These nodules were processed into fertilizer during the First and Second World Wars, when all imports were restricted. The current demand for phosphate in chemical fertilizers is about 50 kt/yr (Agricultural Economics Research Institute, Wageningen).

Diatomites are mainly used in various industrial filters, as grinding and polishing material, as a reactive silica source and for the production of paint, matches and dynamite (Vos & De Wolf, 1988). The only known Dutch exploitable resource, a Holocene lake deposit near Renkum, southern Gelderland, was virtually depleted in a 40-year period around the turn of the 19th century (Laban, 1987). Current import figures for diatomite are unavailable but are expected to be low.

Flint occurring as intercalations and nodules in the chalk of South Limburg was mined extensively during Neolithic times (7000-4000 BP). A total of about two thousand 12-m deep shafts were dug in an area of about 8 acres along the eastern slope of the Meuse valley near the current village of Ryckholt (Felder et al., 1998). These shafts were discovered by the Belgian archaeologist Marcel de Puydt in 1891 and the first one was cleared in 1914. Flint was used to make fire, and to produce axes, scrapers, spearheads, and other types of blades. From Roman times onwards, flint was a by-product of chalk mining and used as building stone.

Exploration and production

Exploration for aggregates

Exploration by Dutch sand and gravel extraction companies is aimed at estimating the tonnage of specific mixtures of sand and/or gravel that can be produced at a site. This requires a high-density drilling campaign (of up to one drilling per hectare) and grain-size analyses of samples per metre drilled. Within such a dense drilling grid, additional geophysical techniques are considered to have limited added value and are seldom used for commercial exploration. Another important exploration objective is to identify cohesive intercalations of clay or peat which may inhibit exploitation with dredging devices. The exploration depths vary between approximately 20 and 40 m, depending on the geological situation and the local policy concerning the depth of extraction pits.

The exploration results are interpreted in terms of the estimated costs of the removal of the overburden and the subsequent extraction and processing of the commodity. These costs, together with those for obtaining the concession area, the required permits, transportation etc., determine the price of the commodity and the viability of the project.

The Dutch government has occasionally commissioned national aggregates exploration studies for policy and planning purposes, or in connection with large-scale hydraulic-engineering projects. Such projects include the exploration for concreting and masonry sand in the North Sea and the combination of hydraulic measures in sand or gravel extraction along the major rivers (RWS, 2004; Van der Meulen et al., 2006). For planning and pre-prospection purposes, TNO – Geological Survey of the Netherlands provides aggregate and other surface mineral resources information online (delfstoffenonline.nl; Van der Meulen et al., 2007, 2013; Maljers et al., 2015, 2020).

While exploration for sand and gravel requires more or less standard geological and sometimes geophysical techniques, exploration for ceramic clay and silica sand may involve various types of specialized chemical and mineralogical analyses (Brijsse & Casier, 1997; Walda, 2000; Van der Meulen et al., 2007). Their interpretation involves the context of production processes and is not discussed here further.

Production of sand, gravel and clay

Most of the sand and gravel produced in the Netherlands is dredged from extraction pits or from open water. Dry extraction, with equipment like draglines, bulldozers and shovels, is used for clay and only occasionally for sand and gravel (e.g. silica sand in South Limburg). Both mechanical (digging), and hydraulic (suction) processes are used for wet extraction. Gravel is usually dredged mechanically, suction being less suited for reasons of wear. Suction dredgers are preferred for sand extraction because of their high production rates and the possibility to use pipelines for transport.

The bucket dredger is one of the oldest types of dredgers. It features a chain of buckets, supported by a ladder, which fill while scraping the bottom (Fig. 18.18a). Bucket dredgers are still in use for coarse-sand and gravel extraction in Limburg. Their main advantage is the possibility to dredge very accurately. Disadvantages are the limitations in depth (down to 20 m) and the noisy operation. Since 1980 a few bucket dredgers have been modernized to reduce the noise and enable extraction from depths down to 35 m.

The wire grab dredger is a versatile excavator suitable for depths down to 100 m (Fig. 18.18b). For sand and gravel extraction, it has largely been replaced by the backhoe dredger which has a higher production rate and allows for more accurate dredging. Backhoe dredgers are based on a digging action towards the machine and can reach depths down to 15 m (Fig. 18.18c).

A stationary suction dredger is the most common device to extract sand from pits (Fig. 18.18d). Suction caus-

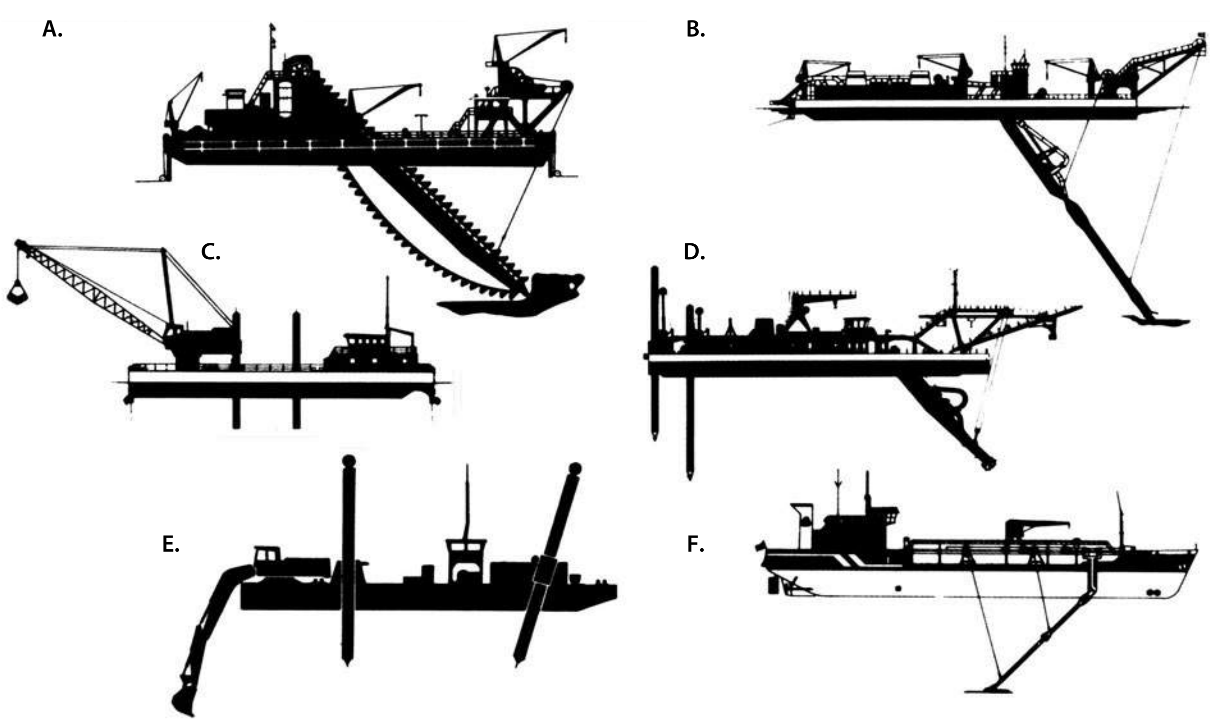


Figure 18.18. Dredging vessels used for sand and gravel extraction: a) bucket dredger; b) wire grab dredger; c) backhoe dredger; d) stationary suction dredger; e) cutter suction dredger; f) trailing suction hopper dredger. Modified from Donze (1990).

Figure 18.19. *Floating aggregates classification unit (Geertjesgolf sandpit, Winssen, Netherlands). Photo by Rudolf Bak.*

es breaching, which generates a flow of sand towards the suction pipe. The process may be disturbed by cohesive sediments, like peat or clay, but such materials can be loosened or penetrated by a suction pipe equipped with water jets. The standard suction dredger is limited to a depth of 30 m, but equipment capable of dredging down to 70 m is available.

A cutter suction dredger dredges cohesive materials using a combination of a cutter head and hydraulic transport (Fig. 18.18e). Cutter suction dredgers are used for the construction and maintenance of harbours and navigation channels, and occasionally for the extraction of sand and gravel.

The trailing suction hopper dredger is a self-propelled vessel which scrapes a thin layer from the bottom and stores the dredged material in its hold (Fig. 18.18f). This device can only be used in deep, open waters. Advantages are the high dredging accuracy, high production rates and the capability to operate in rough waters. Filling sand from the North Sea is extracted with medium-sized hoppers.

After extraction, gravel and sand (except filling sand) are classified by sieving and hydrocyclonage. Floating classification units can be mounted on the dredging vessel or on a separate pontoon (Fig. 18.19), while larger or more sophisticated plants are either mounted next to sand or gravel pits or at central locations where sand from several extraction sites is processed (Fig. 18.20).

Policy context and outlook

Under the Environmental and Planning Act (Anonymous, 2006), extraction permits are issued by provincial authorities or the Ministry of Infrastructure and Water Management for State Waters (*Rijkswateren*). Areas where minerals extraction is considered acceptable are outlined in mineral-extraction plans, which are issued as a part of, or in accordance with regional development plans (*streekplannen* or *omgevingsplannen*). Tree-cutting, noise, turbidity and other environmental impacts associated with extraction may require additional permits from local municipal authorities. Application procedures tend to be time-consuming and may take well over five years.

There is a scale issue in the distribution of burden and benefits that is peculiar to mining: while stable supplies of raw materials for the construction industry are important enough to be considered a matter of national importance, the impacts of their extraction affect only the site and its immediate surroundings. Minerals extraction has been challenged by ever-growing societal resistance since

Figure 18.20. *Aggregates classification plant near Gendt, Netherlands. Photo by Rudolf Bak.*

the 1960s. As a result, provincial administrations have become increasingly reluctant to grant extraction permits and, by the mid-1970s the supply of gravel, concreting and masonry sand and clay for the structural ceramic industry became a matter of national concern (Ike, 2000; Van der Meulen, 2005). The problem was taken up by the Ministries of Transport, Public Works and Water Management, which started preparing for mineral planning guidance at a national level (Anonymous, 1996). As a first step, the Ministry and the provincial administrations agreed on a set of assignments (*taakstellingen*, i.e. amounts of product for which extraction permits are to be granted) for the extraction of gravel, concreting and masonry sand, and clay during the 1980s.

The next step, in the late 1980s, was to prepare the first national policy plan on surface mineral extraction. It stated that the exploitation of surface mineral resources requires planning and co-ordination, as well as better embedding in other policy fields, especially those related to spatial planning (Anonymous, 1989). Policy from then on aimed at sustainable exploitation of the surface mineral resources in order to meet the demand for construction and building materials, at the economical use of such materials and at the maximum use of renewable and secondary materials (Anonymous, 1996, 2001).

Production assignments, though abandoned for clay in 1989, remained the primary policy instrument in mineral planning for about two decades. Up to 1998, the production levels of concreting and masonry sand were kept in approximate balance with the national demand.

However, in 2002 the national government decided to take on a lesser role in mineral supply planning and left supply provision to the market. Mineral planning became a matter of spatial planning and has not been the subject of a specific national policy plan since then. It is mandatory that minerals extraction is conducted in a socially responsible manner and, where possible, contributes to the realization of nature, recreation, lakeside housing and water management.

Future developments

After about two decades of *laissez-faire*, Dutch minerals policy seems to have reached a turning point. The Dutch government now aspires to better consider subsurface resources in spatial planning together with water, under the motto 'water and subsurface guiding' (*water en bodem sturend*; Anonymous, 2022). In addition to geologically determined factors such as ground conditions, implementing this policy requires government to consider geological resources when making spatial plans. The government also defined a housing assignment (*woningbouwopgave*) to counter a persistent housing crisis, which has raised the obvious question whether the considerable amounts of raw materials required for this purpose are available or not. Finally, even though the European Critical Raw Materials Act only concerns one of the minerals treated in this chapter, it has put minerals back on the policy agenda. The question now is whether this is going to add up to better management and stewardship of vital geological resources in the Netherlands.

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Bijlage 2 – Voorkomens zand en grind

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Aggregate resources in the Netherlands

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Abstract

We have built a 3D lithological model of the Netherlands, for the purpose of mapping on-land aggregate resources down to 50 m below the surface. The model consists of voxel cells (1000 · 1000 · 1 m), with lithological composition and aggregate content estimates as primary attributes. These attributes were derived from ~350,000 borehole descriptions. Overburdens and intercalations of cohesive or otherwise non-dredgeable materials were taken into account to define geologically exploitable aggregates within the total stock. We arrive at about 520 · 10^9 m^3 of aggregates occurring in the depth range investigated. Some 50% of this amount is considered geologically exploitable and about 25% would in principle (but largely not in reality) be accessible. Most aggregates resources (~98%) are coarse sand, which is processed for use in concrete, masonry mortars, drains, filters, etc. The total exploitable stock of coarse sand in the depth range investigated amounts to roughly 7500 times the current annual consumption level, and is virtually indepletable. The gravel stock, estimated at some 12 · 10^9 m^3, is small by comparison, and impels a dependency on imports.

Exploitable aggregates occur in all but the coastal provinces. In accordance with current policy changes, the future may show a shift from concentrated production along the upstream Dutch Rhine and Meuse rivers towards a more even distribution of small-sized operations over the country. Fairly large aggregate stocks, that have not yet been exploited to significant extent, are available in the northern extent of the aggregates occurrences.

Keywords: Netherlands, sand, gravel, aggregates, resource assessment

Introduction

Aggregates, i.e. granular mineral materials, are used in construction and by the building-materials industry. Dutch production amounts to about 75 Mt/a and includes about 50 Mt/a of fine sand, 20 Mt/a of coarse sand and 5 Mt/a of gravel (Van der Meulen et al., in press). The Netherlands are not self-supporting for aggregates; the ever-growing net-import level is currently between 30 and 40 Mt/a. An important reason for this is restricted access to resources. The Dutch population density (481 inhabitants per km^2 in 2004) ranks among the highest in the world, and more than 85% of the Dutch land surface is developed. Land-based aggregates extraction, which usually transforms land into a water body, is therefore prone to raise land-use conflicts and seems to be more controversial than in other countries (Van der Meulen et al., 2003; in press).

The Dutch Ministry of Spatial Planning, Housing and the Environment has recently designed a so-called building raw materials assessment ('bouwgrondstoffentoets'; Anonymous, 2004), in order to arrange for a certain level of access to surface mineral resources. Spatial plans have to be evaluated (i) in terms of the effects on mineral supplies, (ii) for the accessibility of resources of scarce minerals to future generations, and (iii) for the possibilities to embed mineral extraction into projects which have other primary goals (e.g.

hydraulic engineering, nature development). Note that the Netherlands has very few mineral resources: only aggregates, clay, peat, silica sand and carbonate rocks are quarryable. The assessment defines 'scarce minerals' within this group of minerals, and refers to each of them except for peat, which is not quarried at present, and fine sand. The other minerals can either be geologically scarce (e.g. high quality silica sand), or scarce on the market, mainly because of a restrictive policy for issuing extraction permits (e.g. coarse sand).

The building materials assessment is currently in the process of being adopted by the mineral planning and permit-issuing authorities, i.e. the Ministry of Transport, Public Works and Water Management where state waters ('rijkswateren') are concerned, and the provincial administrations in all other cases. Irrespective of the shape the building raw materials assessment will take, it will somehow have to rely on geological information. We present new maps of aggregate resources in the Netherlands, and estimates of the sizes of its stocks down to 50 m below the surface. Scale and resolution are adapted to a representation on a national scale. The approach taken can however be applied on regional and local scales and, hence, to future building raw materials assessments.

Geological setting

The Dutch shallow subsurface consists almost entirely of Quaternary clastic deposits, deposited in fluviatile to shallow marine sedimentary environments (Fig. 1, 2). Most of the sediments have been supplied by (the predecessors of) the Rhine and Meuse rivers, and by the former Eridanos river system which had a drainage area covering Northern Germany and Scandinavia (De Mulder et al., 2003). They grade, on average, from coarse-grained in the southeast and east towards fine-grained in the western and northern parts of the country and the North Sea.

Pleistocene glaciations have shaped the area north of the Rhine-Meuse delta (De Mulder et al., 2003). The course of latest Pleistocene to recent Rhine and Meuse channels has especially been determined by the Saalian ice-sheet and the ice-pushed structures it has produced. The most important ice-pushed ridges occur in the provinces of Utrecht and Gelderland; the associated ice-scoured glacial basins are located on their concave east and north sides. Sediment distribution south and southeast of the Rhine-Meuse delta, in terms of both quantities and lithofacies, has been governed by north-westward tilting,

Fig. 1. Geological map of the Netherlands showing provincial boundaries and aggregate extraction sites (active, abandoned and planned; circle size proportional to extraction size). Geological information modified from Weerts et al. (2004).

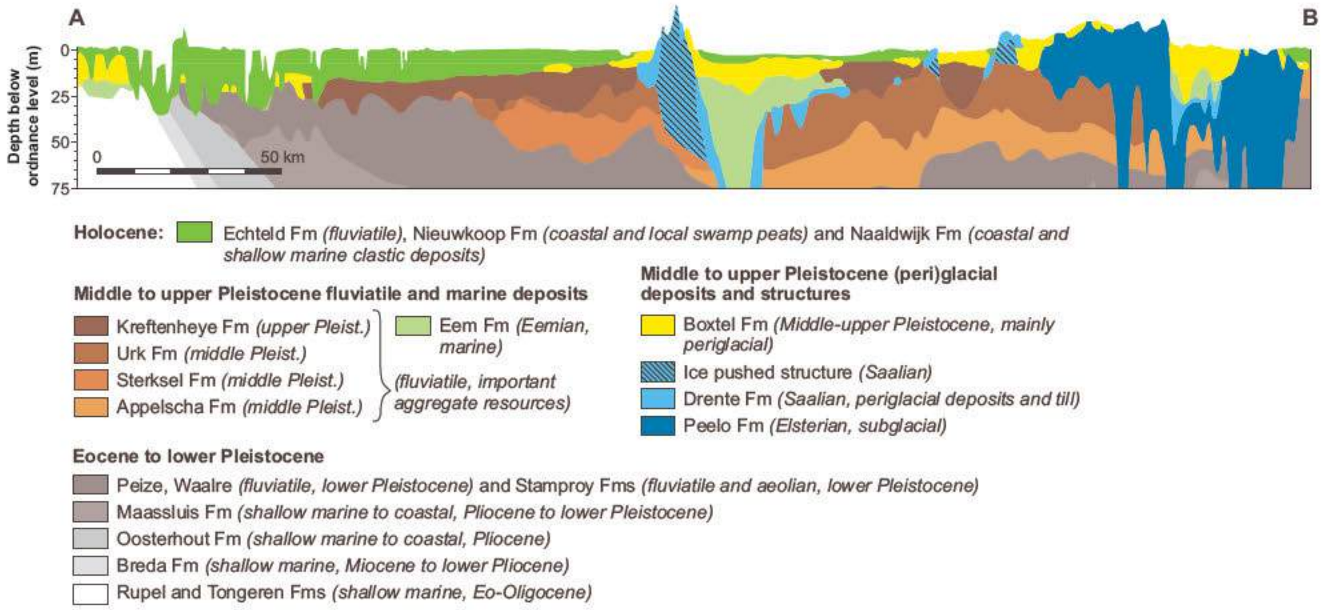

Fig. 2. Geological cross section from Zeeland to Groningen (see Fig. 1 for section line). It has been constructed by intersecting depth grids of formation boundaries (1 : 250,000), which have been obtained in the 3D geological mapping program carried out by TNO Built Environment and Geosciences – Geological Survey of the Netherlands. All formations referred to are cf. De Mulder et al. (2003).

associated with uplift of the London-Brabant massif, and by NW-SE trending horst-graben structures.

Aggregate commodities: geological data vs. industrial specifications

The grain size parameter in available data

Aggregates, except for filling materials, are primarily defined by their grain size distributions. Our aggregates mapping is based on borehole data in DINO, a digital archive of subsurface data developed and maintained by TNO Built Environment and Geosciences – *Geological Survey of the Netherlands* (for database specifications see Kooijman, 2003; Peersmann, 2005). Sand descriptions usually include estimated or measured median grain sizes, either as a class (extremely fine, very fine, etc.) or a discrete value (M63, i.e. the median grain size of the sand fraction). Gravel occurrences or admixtures are described in similar ways, although quantifications or classifications occur somewhat less frequently. Only a negligible share of the approx. 380,000 standardized borehole descriptions in DINO includes full grain size distributions, so the sizes of national aggregate stocks can only be approximated.

Aggregate yield calculations

In order to calculate aggregate yields from lithological data, we have had to use median grain size data pragmatically. Assessments of the application possibilities of sands first requires a distinction between fine and coarse categories (Van der Meulen et al., in press). Fine sand is used as filling material. As fine sand can be found virtually anywhere in the country and filling sands supplies have never imposed problems, we do not further elaborate on its stocks. In fact, common aggregate definitions usually exclude landfilling materials. Coarse sand is used as an aggregate for more advanced purposes, i.e. for the production of concrete and masonry mortars, in drains, filters etc.

In the Netherlands, coarse sand commodities are usually jointly referred to as 'concrete and mortar sand' (*'beton- en metselzand'*; NEN, 1991; 1999). A fairly common first order estimator for reserves of concrete and mortar sand is the amount of so-called sand 30/92 that can be produced at a site, i.e. a sand with 30 and 92 cumulative mass percents retaining on the 1 mm and 250 μm sieve, respectively. In approximate accordance with this, we do not consider extremely fine, very fine and moderately fine sands to be concrete and mortar sand resources (Table 1). Secondly, we assume that 50% of moderately coarse and very coarse sands, i.e. the coarse half of their grain size populations, can be used in concrete and mortar sand. Finally, we assume a 100% grade for extremely coarse sands, as indeed most concrete and mortar sands would geologically be classified as such. We expect that any type of gravel can be entirely used as or processed into an aggregate: fine gravel as an admixture in concrete and mortar sand, coarse gravel as such. We feel that more sophisticated ways to calculate aggregate yields from lithological descriptions are not relevant on national scale assessments.

Distinguishing between gravel and sand commodities

A subdivision of aggregates into gravel and sand commodities is hampered by the differences in their industrial and geological

Table 1. The application of natural sand and gravel as aggregates according to their M63 value. Category and class definitions are cf. Anonymous (1989; 1990); CMZ = concrete and mortar sand. See text for further explanation.

Category	Class	Median grain size				Aggregate yield	
		(≥)		(<)			
Fine sand	Extremely fine	63	–	105	µm	0%	
	Very fine	105	–	150	µm	0%	
	Moderately fine	150	–	210	µm		
Coarse sand	Moderately coarse	210	–	300	µm	50%	(CMZ)
	Very coarse	300	–	420	µm		
	Extremely coarse	420	–	2000	µm	100%	(CMZ)
Gravel	Fine	2	–	5.6	mm	100%	(CMZ, gravel)
	Moderately coarse	5.6	–	16	mm	100%	(gravel)
	Very Coarse	16	–	63	mm		

definitions. The Dutch sediment and soil classification system (Anonymous, 1989; 1990) is based on a set of three ternary diagrams. Sediments are classified according to gravel content (diagram 1), organic matter content (diagram 2), and the relative contents of the sand, silt and clay fractions (diagram 3). In this system, gravel is a granular material with ≥30% of gravel particles, i.e. particles with a diameter of ≥2 mm. The more straightforward industrial definition of gravel is a natural granular material with application-dependent lower (generally 4 to 8 mm) and upper limits (generally 16 to 32 mm) to its grain size distribution. Sand is defined similarly, with a lower limit of 63 to 125 µm and an upper limit of 4 to 8 mm. Because of these differences we can not accurately distinguish between gravel and sand commodities on lithological criteria alone. We primarily assess aggregate resources, in which coarse sand and gravel are lumped, and give an indication of gravel resources as a subcategory by applying a geographical search criterion.

Modeling approach

Model setup and data selection

As a first step in the resource assessment we have built a 3D-lithological model of the Netherlands (excluding the North Sea) down to a depth of 50 m below the surface. This depth range comprises aggregate resources that are currently exploited: most aggregates pits are between 25 and 40 m deep. The model is based on a so-called voxel grid which divides the model space into equal-sized rectangular cells. The model volume covered by a cell is characterized by a number of lithological cell attribute values, which have been either obtained or derived from borehole descriptions in DINO. We used cells with a surface area of 1000 · 1000 m and a thickness of 1 m, which resulted in a model of 50 layers of 40,769 cells.

Available borehole descriptions – in principle all of the ~380,000 in our archives – show a wide range in quality, depending on the drilling method, the original purpose of drilling, drilling personnel qualifications, whether descriptions have been made in the field or in the laboratory, etc. The number of drillings precludes a manual assessment of these factors, so we have used the average thickness of lithological description intervals as a quality proxy. We consider an average thickness >3 m to be indicative of insufficient quality for our purposes; such data are discarded from the model data set. The 3 m limit is a value of experience: from earlier work it is known to exclude the most unreliable cases, such as third-party field descriptions of water drillings.

The application of the quality criterion resulted in the selection of 351,161 drillings (Fig. 3). The average number of drillings per km^2 (i.e. per cell) decreases from 8.6 for the upper model layer to 0.2 for the lower layer. The average data-quality also decreases with depth: the deeper a drilling, the greater the chance that (cheap) suction or airlift drilling methods were used. As these methods tend to underestimate the shares of the fine fractions, aggregate yields may tend to be increasingly overestimated with depth.

Model characteristics

The primary model cell attributes are its shares of gravel, sand, clay/loam, peat/gyttja and 'other' material (e.g. the chalk occurring in the southernmost part of the country), calculated from borehole data. The shares of the lithologies that we distinguish were interpolated over cells lacking drilling data, using linear kriging (Fig. 4; e.g. Deutsch & Journel, 1998). As a next step, aggregate yields for each cell were calculated using the criteria given in Table 1. Aggregate yields were then interpolated over cells which lack grain size information or drilling data altogether, and multiplied with interpolated shares of sand and gravel lithologies in order to obtain absolute values.

The above approach accounts for the grade of aggregate resources. Their exploitability also depends on the thickness

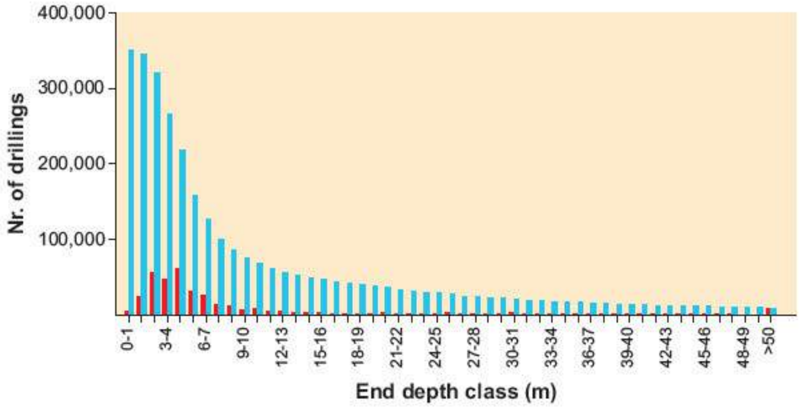

Fig. 3. Red bars: histogram of the end depth of the drilling data used in our study. Blue bars: the total number of drillings available to a model layer in the depth range indicated. A total of 351,161 standardized borehole descriptions were selected from a total of ~380,000, using a quality proxy explained in the text.

of the overburden that would have to be removed, and of intercalations of fine grained material which may hamper the extraction process (generally some dredging technique). In order to address these factors, routines were used which analyze vertical cell stacks. An overburden routine discards aggregate yields if covered by more than 5 m of clay, loam, peat or gyttja, i.e. the shares of these materials times the thickness of the cell stack above the first aggregate occurrence. An intercalation criterion, acting from 5 m below the surface downwards, adds up the amount of these materials present and discards aggregate yields below intercalations with a cumulative thickness of 2 m or over.

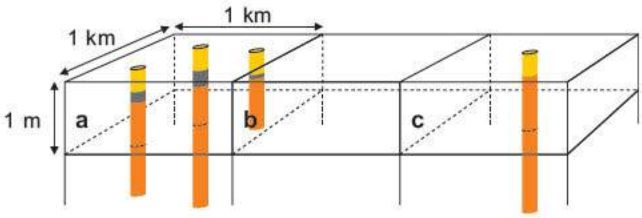

Fig. 4. Model setup, illustrated by three hypothetical cells from the upper model layer. For cell a, the shares of distinguished lithologies are obtained by averaging the layer properties in the appropriate depth range of three available drillings. The properties of cell c correspond to those of the one available drilling. The attributes of cell b (i.e. lithology and aggregate yield) are obtained by linear kriging between cell a and c. The zero-level in the model space corresponds to land surface.

Results

General

Fig. 5 (left 3 panels) shows cumulative aggregates thicknesses down to 10, 30 and 50 m below the surface (see Fig. 6 for an appraisal of the underlying model). The results clearly fit the aforementioned general geological trends (Fig. 1, 2). In their northern extent, aggregates predominantly occur in ice-pushed structures, and are scarcer, absent or covered in the associated glacial basins which generally have fine-grained infillings. In the Rhine-Meuse delta, aggregates occurrences are mainly upper Pleistocene river sands. The east-to-west decrease of aggregate volumes is a clear reflection of both downstream fining and a westward-thickening overburden. In the south, aggregates occurrences are arranged in the NW-SE trending horst-graben structures.

The total aggregate volume down to 50 m below the surface is estimated at ~520 $\cdot$ 10^9 m^3 (Fig. 7, 8). Some 240 $\cdot$ 10^9 m^3 of this amount is considered exploitable according to the above geological criteria. Fig. 5 shows that especially the aggregates occurrences in Zuid-Holland are not considered exploitable, due to their overburden. In fact, the westernmost Dutch extraction of concrete and mortar sand occurs just east of the Utrecht – Zuid-Holland boundary, at the westernmost extent of the central Dutch aggregate resources according to our exploitability criteria (middle and lower right panels of Fig. 5). About 80% of the exploitable aggregate resources occur in 5 out of 12 provinces (i.e., Limburg, Drente, Noord-Brabant, Overijssel and Gelderland; Fig. 9), and about half are situated below built-up areas or nature reserves, and are therefore in principle inaccessible. Note that a 50% accessibility is probably greatly overestimated. First, we have not taken into account the access limitations presented by scattered buildings and infrastructure in open country. More importantly, various planning restrictions may apply to aggregates extraction, even outside protected nature or landscapes.

Gravel resources

Most of the Dutch aggregate resources consist of coarse sand, with gravel as an admixture or intercalation. Shading in Fig. 5 corresponds with the occurrence of coarse gravel, which have been mapped for national mineral planning purposes (i.e. for Anonymous, 1994; 2002; note that national mineral planning has been abandoned in 2003; Van der Meulen, 2005). The area encompasses the most important Dutch gravel production sites, that are mainly situated along the upstream Meuse river. The aggregate content of this area down to 50 m below the surface is about 12 $\cdot$ 10^9 m^3, which amounts to about 25% of the aggregate resources in Limburg and to about 2% of the Dutch total. Again, about half of this amount is considered geologically exploitable (Fig. 10).

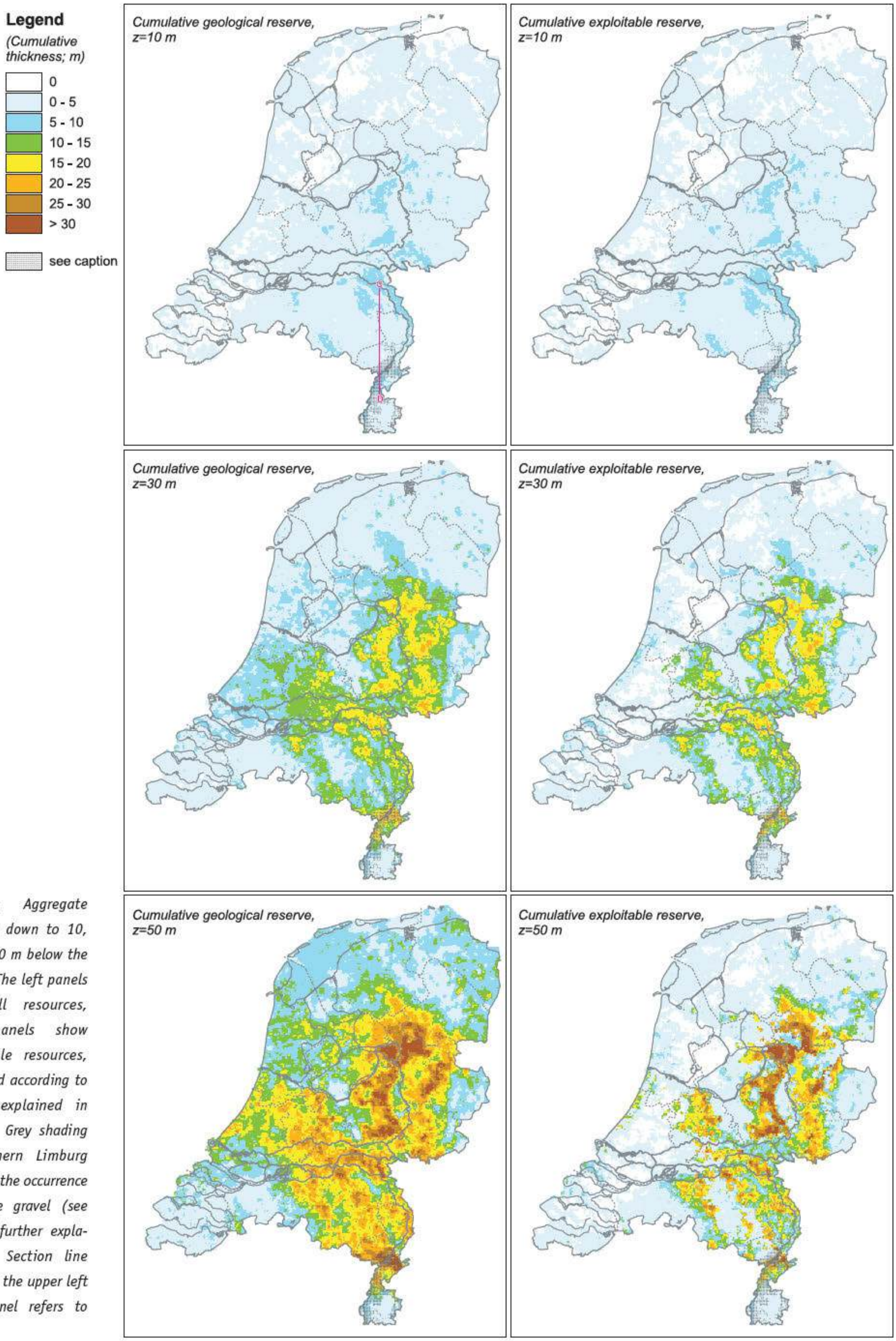

Fig. 5. Aggregate resources down to 10, 30 and 50 m below the surface. The left panels show all resources, right panels show exploitable resources, calculated according to criteria explained in the text. Grey shading in southern Limburg indicates the occurrence of coarse gravel (see text for further explanation). Section line (c - d) in the upper left hand panel refers to Fig. 6.

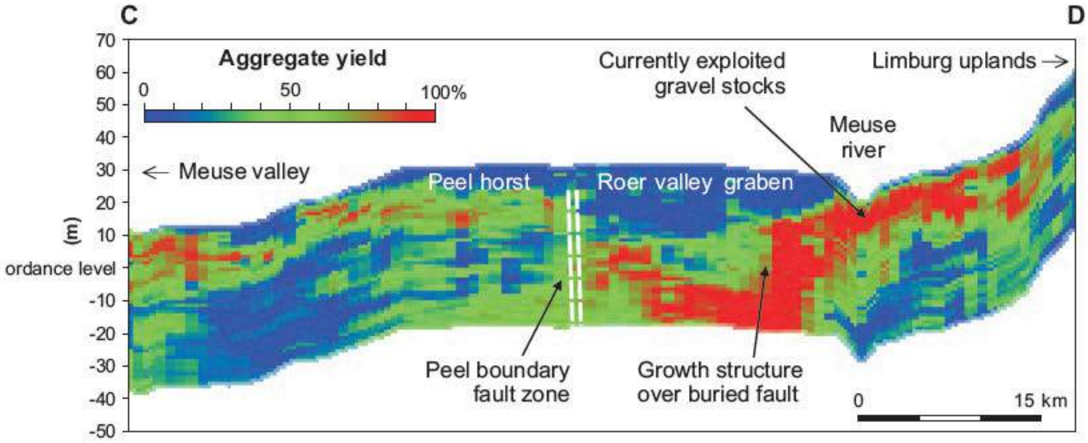

Fig. 6. Cross section through the model space in Limburg (see Fig. 5 for section line). Note that aggregates distribution is consistent with geological structures, even though they have not been imposed to the model.

In the south of Limburg, gravel occurs as a relatively thin cover on a substrate of uplifted Upper Cretaceous to Miocene units (Fig. 5, see also Fig. 1). This is clearly reflected in Fig. 11, which shows that the aggregate content decreases with depth, as opposed to the general trend in Fig. 8.

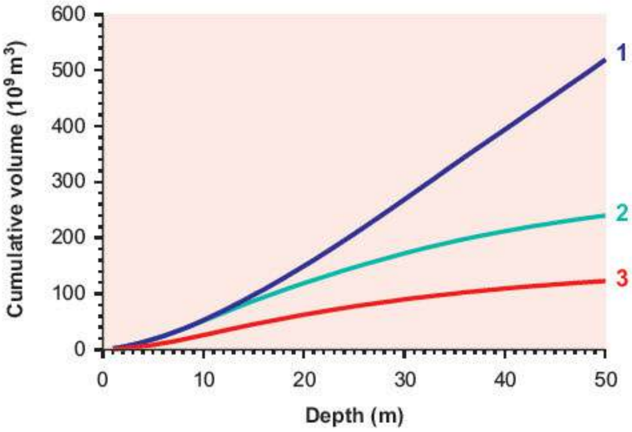

Fig. 7. Cumulative aggregates volumes down to 50 m below the surface: 1) all aggregates; 2) geologically exploitable aggregates (see text for explanation); 3) idem, disregarding aggregates below built-up areas and protected nature.

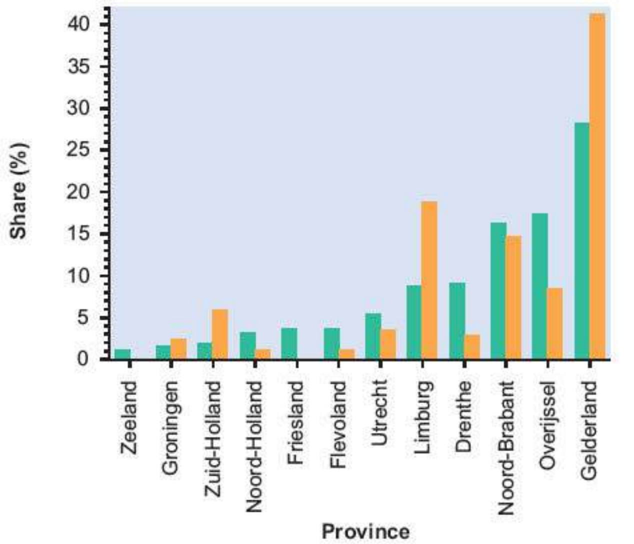

Fig. 9. Green bars: the distribution of geologically exploitable aggregate resources over the provinces (depth range 0 - 50 m). Orange bars represent the distribution of provincial production assignments for concrete and mortar sand, i.e. amounts of product for which permits are to be granted in the period 1999 - 2008. Provincial assignments and resources seem miscorrelated; they have, however, been based on a combination of resource estimates and ease of transport per ship.

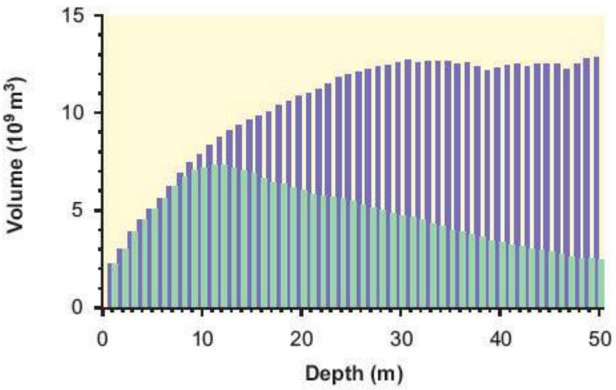

Fig. 8. Aggregates per meter interval down to 50 m below the surface, blue bars: all aggregates; green bars: geologically exploitable aggregates (see text for explanation).

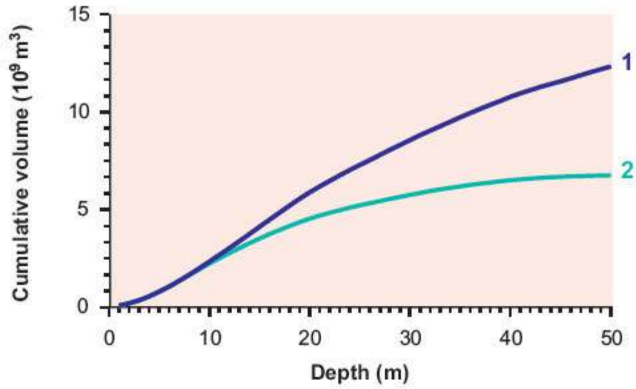

Fig. 10. Cumulative gravel volumes down to 50 m below the surface: 1) all gravel; 2) geologically exploitable gravel (see text for explanation).

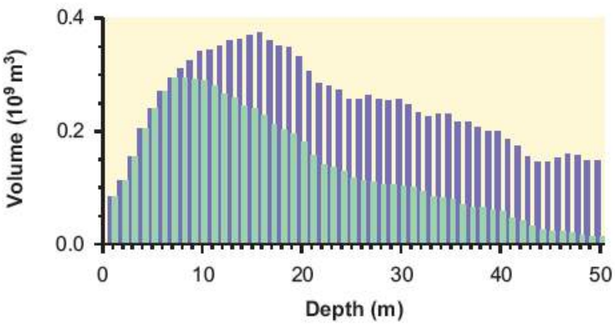

Fig. 11. Gravel per meter interval down to 50 m below the surface: blue bars all aggregates; green bars geologically exploitable aggregates (see text for explanation).

Concluding remarks

General

Aggregates occur abundantly in the eastern and southern parts of the Netherlands. Some 98% of the aggregates is coarse sand, the size of the geologically exploitable resources corresponds to roughly 7500 times the current annual consumption of concrete and mortar sand. The geologically exploitable gravel resources in southern Limburg amount to some 150 annual consumption equivalents, of which probably only a couple of tens are accessible. Hence, for coarse aggregates, some level of dependency on imports seems inevitable.

Home production

Mineral planning until the year 2003 has resulted in a concentration of large-scale aggregates extraction sites along the Rhine and Meuse in the provinces of Noord-Brabant, Limburg and Gelderland. These sites were developed for national supplies, i.e. in order to provide provinces lacking resources with aggregates. Under the current policy regime, such large-scale sites will probably not be permitted anymore. The embedding of extraction in projects with other goals, which is both stimulated by the aforementioned building raw materials assessment and envisaged as the future modus operandi by the extractive industry, will most likely also result in a downsizing of individual operations. Altogether, the future home production of aggregates will probably come down to a larger number of smaller projects, that will be more evenly distributed over the country. A part of the production may well shift to Overijssel and southern Drenthe, where fairly large aggregate stocks are present which have not yet been exploited to significant extent.

Future supplies

As it is for the first time in two decades that production has stopped being regulated, the effects of the recent Dutch policy changes cannot not be predicted. Production figures show that the production of sand aggregates in 2003 was 25% below the average level of 1996 - 2000. Unpublished provisional data suggest that this unprecedented drop has continued to date, seemingly with no real supply problems. In the coming years, production will probably stabilize at some unknown lower level. Available forecasts suggest that consumption will remain stable or increase slightly (e.g. Van der Meulen et al., in press), so eventually the net imports required may well exceed the production possibilities in the countries that currently export to the Netherlands, especially in the German federal state of North Rhine-Westphalia. All the alternative supply options, e.g., production from lower grade marine resources, deep(er) extraction, or imports from more remote areas, will probably be significantly more expensive.

The question is how much more the Dutch building industry and its commissioners are ultimately prepared to pay for raw materials, knowing that vast resources are in principle available in the country. Large transport distances for low-cost bulk commodities such as sand may also raise some concerns as to the sustainability of the path chosen by Dutch policy makers. Dutch aggregates resources will therefore probably keep being exploited. The embedding concept in the building raw materials assessment was designed for more acceptable forms of exploitation; our study basically addresses the localization aspects of such exploitation.

Application possibilities

Even though the approach taken has been pragmatic rather than sophisticated, our study has significantly improved our appraisal of Dutch aggregate resources. Most limitations of our modeling methods and yield calculations can be addressed when working on regional scales, handling less data. Examples of this include the quality proxy for borehole descriptions, and the overburden and intercalation criteria, which can both be tuned to regional geological characteristics such as the sedimentary setting and the tectonic history. The approach is intended to be used interactively, allowing aggregate resources and their geological exploitability to be defined by end-users.

Disclaimer and acknowledgements

Although the authors adhere to its basic principles, this study does not formally comply with the Code for Reporting of Mineral Exploration Results, Mineral Resources and Mineral Reserves (Anonymous, 2001). In the terms of this code, our study would classify as a reconnaissance mineral resource, apt for mineral or spatial planning purposes by the government. Note that our results are not to be used for the purpose of (a) informing investors or potential investors and their advisers or (b) satisfying regulatory requirements. The authors wish to thank their colleague Wim Dubelaar (TNO, Utrecht, NL), and Mike Petterson (BGS, Keyworth, UK) and an anonymous reviewer for helpful suggestions.

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Bijlage 3 – Voorkomen klei

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Clay resources in the Netherlands

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Abstract

Clay is a common lithology in the Dutch shallow subsurface. It is used in earth constructions such as dikes, and as raw material for the fabrication of bricks, roof tiles etc. We present a new national assessment of Dutch clay resources, as part of a project that provides mineral-occurrence information for land-use planning purposes. The assessment is based on a 3D geological model, which consists of voxel cells with lithological composition as primary attribute, and has been obtained by interpolating data of more than 380,000 digital borehole descriptions. The occurrence of shell material and the extent to which clay is peaty were used as quality attributes, enabling us to tentatively distinguish between clay that is potentially suitable as ceramic material, and clay that is not.

As clay is extracted using dry (i.e. non-dredging) techniques, the model space has been dimensioned to fully encompass the unsaturated zone. A high-resolution model (with voxel cells of 250 · 250 · 0.2 m), based mainly on abundant, good-quality hand drillings, was constructed down to 3 m below the surface. This depth range suffices for clay-resource assessments in the lowlands, which have relatively high groundwater levels. Cells from a lower-resolution model (250 · 250 · 1 m, based on fewer data) were added to reach appropriate depths in upland areas.

We arrive at about 42.1 km^3 of clay occurring in the model space (land areas only). Clay occurs mainly in the coastal domain and below the Rhine and Meuse river plains. Geological exploitability has been assessed within the unsaturated zone, taking overburden and intercalations with non-clay materials (especially peat) into account. The resulting exploitable stock is 12.3 to 18.0 (± 2.0) km^3; an estimate in which the main source of uncertainty is presented by a lack of proper groundwater-table data. This amount equates to roughly 6000 annual consumption equivalents. Even when considering that the larger part of the clays is unsuitable for firing, and about one quarter is situated below built-up lands or nature preserves, clay is not a scarce resource in the Netherlands and supplies should present no problem in the near future.

Keywords: Netherlands, clay, resource assessment, building materials, construction materials, structural-ceramics industry, earth constructions

Introduction

Clay is a versatile mineral raw material: malleable when moist, cohesive after drying, and rock-hard when fired. It is applied as such in earth constructions that are durable and impermeable to water, and it is used as raw material for ceramic-product manufacturing. In the Netherlands, clay occurs abundantly and it is accordingly important as building and construction material. Even though the last decades have seen an ever-increasing use of concrete, clay bricks and roof tiles still determine the face of any Dutch town. Current Dutch clay consumption is 2 to 3 Mt/a (Fig. 1). About two thirds of this amount is used by the structural-ceramics industry, and one third is used in construction, mainly for dike building and maintenance (Van der Meulen et al., in press). The Netherlands is virtually self-supporting for clay (Van der Meulen et al. 2003a). Small amounts are imported, mainly from Germany, in order to supplement Dutch ceramic clays with materials having some special property.

The Dutch Ministry of Spatial Planning, Housing and the Environment has recently introduced a so-called building materials assessment (*'bouwgrondstoffentoets'*; Anonymous, 2004; Van der Meulen, 2005a), in order to arrange for a certain level of access to sparse surface mineral resources. It involves

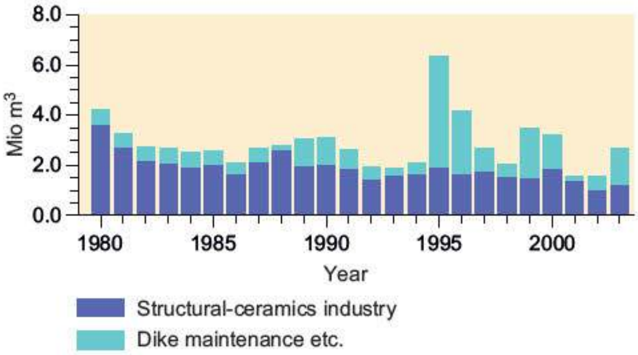


Fig. 1. Dutch clay production between 1980 and 2003 (Van der Meulen et al., In press). The peak in the mid-1990s reflects a dike-reconstruction programme, which was undertaken after imminent river floods in 1993 and 1995.

the identification of mineral resources when preparing for building or land-reconstruction projects (that is, outside areas that are already built-up), and it requires taking mineral resources and interests into consideration in the planning process (e.g. Van der Meulen et al., 2004, 2005b). The aim of the assessment is to avoid (unintended) sterilisation of resources, and to stimulate their exploitation in conjunction with the project that is assessed. Clay for the structural-ceramics industry is one of the mineral types that are considered scarce.

Conducting the assessment requires the use of geological information. We present a new assessment of clay resources in the Netherlands, including estimates of the size of the exploitable stocks. The results of this study will be used for '*Delfstoffen Online*' (Minerals Online): a nation-wide, web-based minerals information system that is currently being developed as a tool for the building materials assessment (TNO 2007a).

Geological setting

Most superficial clays in the Netherlands are of Holocene age, and deposited in fluviatile to shallow marine sedimentary environments (Fig. 2). Older clays occur at or near the surface in the uplands of the provinces of Limburg (Tertiary fluviatile and marine clays), Gelderland and Zeeland (Rupelian marine clays). Quaternary brook deposits in Noord-Brabant, Gelderland, Overijssel and Limburg are resources of secondary importance, which were exploited mainly historically, when the structural-ceramics industry was spread all over the country, supplying local markets. Pleistocene loess deposits in Limburg, no clay

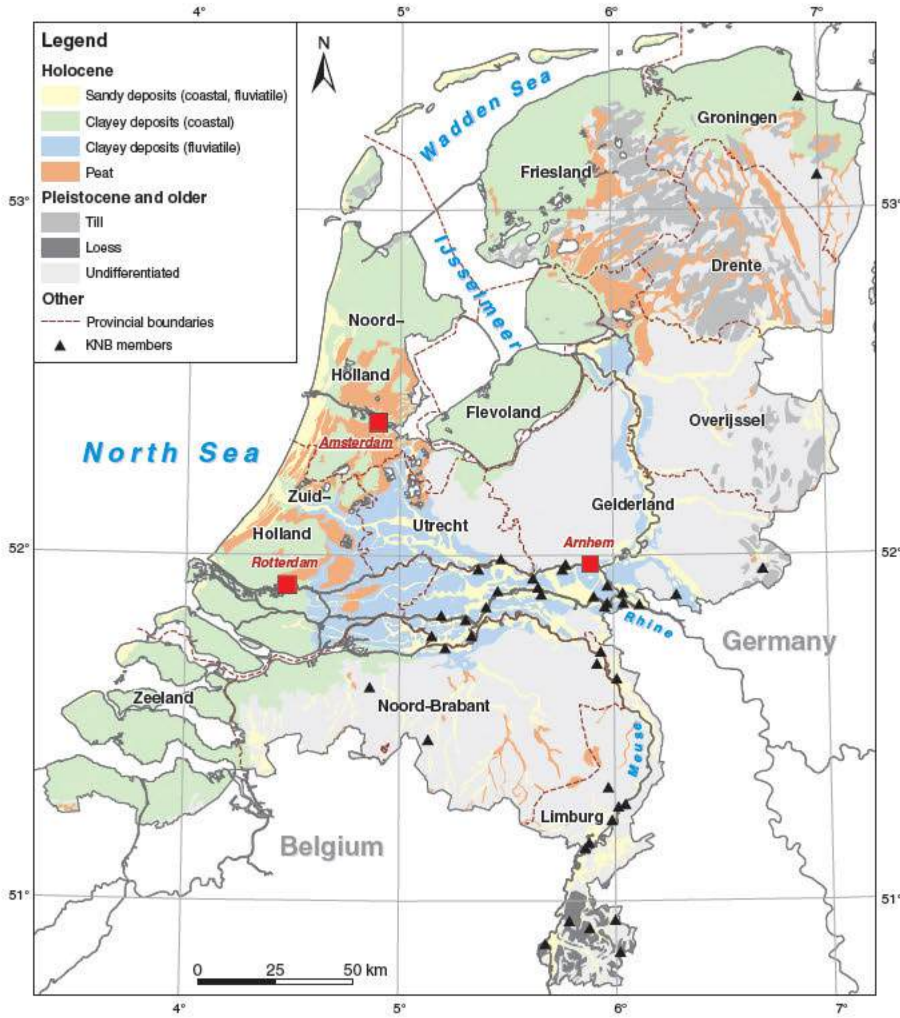


*Fig. 2. Simplified geological map of the Netherlands, modified from Weerts et al. (2004). 'KNB members' belong to the Royal Association of Dutch Brick Producers (*Koninklijk Verbond van Nederlandse Baksteenproducenten*, based in* Velp*), which represents the larger part of Dutch structural-ceramics industry.*

resource in the geological sense, are exploited on a minor scale for a variety of purposes, including ceramic-product fabrication.

At present, Dutch brick and roof-tile producers extract about two-thirds of their clay along the rivers Rhine and Meuse (Sigmond et al., 2001). Clay is deposited at relatively high rates within the confinement presented by the lowlands' river dikes, and by the valley flanks of the upstream Dutch Meuse (e.g. Van der Meulen et al., 2006).

Data and criteria

Borehole data

The present clay-resource assessment is based mainly on borehole data in DINO, the Dutch national database for geological data and information, developed and maintained by the Geological Survey of the Netherlands (Kooijman, 2003; Peersmann, 2005). It has the advantage of being the single largest dataset of its kind in the country, offering national coverage. DINO currently contains more than 380,000 borehole descriptions, i.e. ~9 per km^2 on average (Fig. 3). This number includes our own boreholes, most of which were drilled for geological mapping purposes, and third-party data. All of the descriptions were selected for processing. While the available data are satisfactory for regional to national-scale work, their quality presents some limitations to our study in terms of accuracy and definition issues.

Assessing resources with non-dedicated data

Clay is relatively easy to identify in the field, but there are several formal and informal definitions that differ considerably (Van der Meulen et al., 2003b). Clay may be defined according to grain size (e.g. the share of lutum: particles <2 µm), mineralogy (clay-mineral association) or geotechnical behaviour (cohesive, plastic when moist, etc.).

Dutch structural-ceramics industry primarily defines clay by the share of particles <10 µm, a range that comprises not only the lutum fraction, according to which clay is defined geologically, but also the fine silt fraction. Beyond that, a number of physical and chemical properties are relevant for raw-material characterisations. Modern production efficiency and quality control require optimised production processes and materials, which have to comply with narrowly defined specifications. Rather than firing available clay from local resources, as was customary in the past, clays from different locations or stratigraphic levels are mixed to meet such specifications. Accordingly, assessing the quality of clay as ceramic material has come to be a rather specialised undertaking. The industry funds a dedicated research institute (TCKI, based in Velp), which makes such assessments in the context of the complete ceramic-product process chain: raw materials properties and handling, drying and firing processes, and end-product specifications such as strength, durability, colour and texture. These are determined largely by the clay chemistry and mineralogy, and by the sand and organic-matter contents (Van der Zwan, 1990; Van Wijck, 1997; Table 1). Customer demands for certain colours or textures are important to the industry, and these are determined mainly by the iron and carbonate contents. Shells, calcareous nodules, peat, plant debris or rootlets are deleterious impurities that increase the chance of failure during production or use.

The quality of borehole data in DINO reflects the original purpose of the drilling, the drilling and description methods, the qualifications of the personnel involved, etc. Even in the best category, however, the descriptions do not meet industrial standards for clay-prospecting. Not all relevant parameters are included, and most of the ones that are were not determined with sufficient accuracy. Shares of lutum, silt and sand, for instance, are commonly estimated grain-size or admixture classes, rather than discrete values determined by laboratory analyses. Organic matter and carbonate contents are either

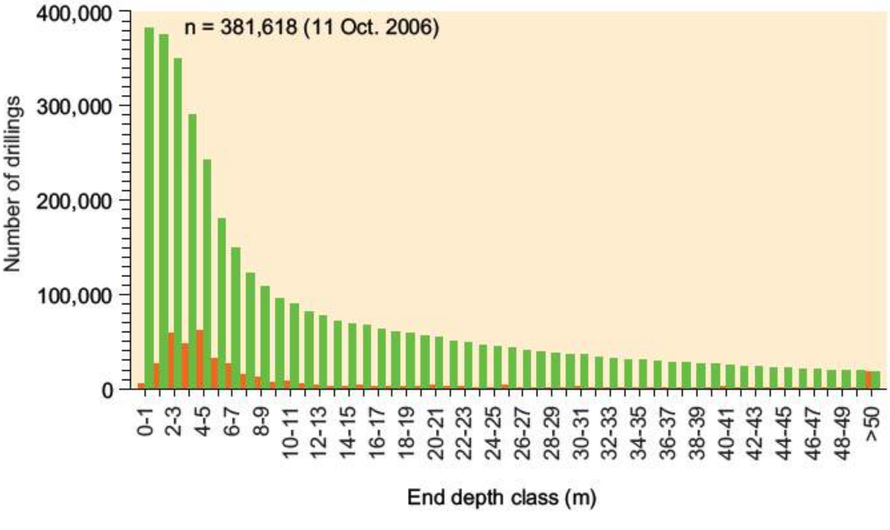


Fig. 3. Orange bars: histogram of the end depth of the drilling data used in our study. Green bars: the total number of drillings available per metre interval.

Table 1. Approximate requirements for clay in the structural-ceramics industry and for dike maintenance. Note that clay in the industrial definition may include loam (/silt). Modified from Van der Zwan (1990).

Application	Share of grain-size fraction (% m/m)					C-org	$CaCO_3$
	Lutum	<10 µm	63 - 250 µm	≥250 µm	Sand	(% m/m)	(% m/m)
Roof tiles		50 - 57	<20	<40		<3	<25
Bricks	40 - 42	<20	<40		<3	<25	
Extruded products		40 - 55	<20	<40		<3	<25
Dike maintenance	18 - 40				<40	<3	

not quantified, or given as abundance classes based on visual estimates. The number of chemical analyses in our database is negligible. Because of these limitations, we focussed on properties that inhibit ceramic-product fabrication, rather than attempting to map quality parameters. This approach is consistent with the scale and purpose of our assessment, which is tuned to regional planning and pre-prospecting.

Clay specifications for earthworks are related largely to the desired cohesiveness and impermeability, and are less stringent than those for the ceramic industry (Table 1). Locally extracted clay is used wherever possible, so for this application we expect to provide sufficient information with the combination of resource distribution and clay properties that can be derived from non-dedicated geological data.

Resource definition

In principle, clay in our database is defined according to NEN 5104 (Anonymous, 1989, 1990). This official Dutch sediment-sample classification system is based on a set of three ternary diagrams (Fig. 4). The first of these, in which the shares of the gravel (≥2 mm), sand (63 - 2000 µm), and lutum + silt (<63 µm) fractions are plotted, is used to determine whether or not a sample classifies as gravel. The second diagram, of the shares of organic matter, lutum, and sand + silt, is used to determine whether or not a sample is peat. If not, the third diagram is used to distinguish between sand, loam and clay (note that silt is no sediment type in the Dutch classification; the term refers to a fraction only).

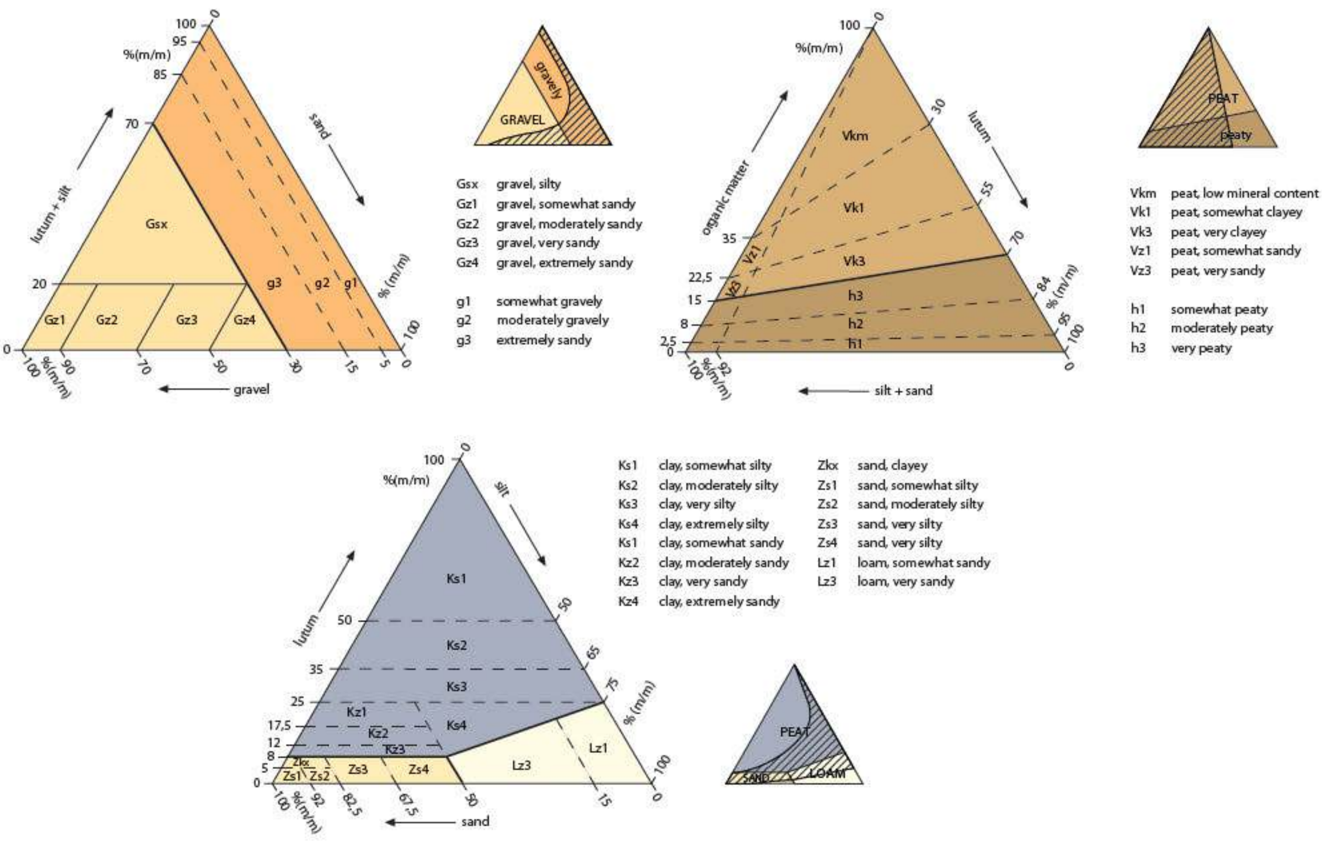


Fig. 4. Ternary diagrams of the Dutch soil classification system, modified from anonymous (1989, 1990); see text and Van der Meulen et al. (2003b) for explanation. Hatching indicates naturally occurring sediments.

As raw material, clay may include sediments that geologists would classify as loam (or silt) rather than clay. Our inventory has to be based on geological data and classifications, but keeping the industrial definition of clay in mind. In the terms used in our database, we consider clay, sandy clay, loam (which includes loess) and sandy loam to be clay resources. We distinguish between fine and coarse resource categories, i.e. clay s.s. and the other clayey lithologies, respectively.

Modelling approach

Model setup

Van der Meulen et al. (2005) presented a 3D lithological model (further referred to as 'aggregates model'), which was built for a national re-assessment of aggregate resources. We refer to this publication and references therein for the generalities of data handling and model building. The modelling procedure, a 3D interpolation of drilling data into a voxel model with pertinent cell attributes (i.e. the shares of gravel, sand, clay/loam, peat and 'other' material), is summarised in Figure 5. The main effort of the present study has been put in dealing with the limitations of the aggregates model for use in a clay-resource assessment (resolution and confidence).

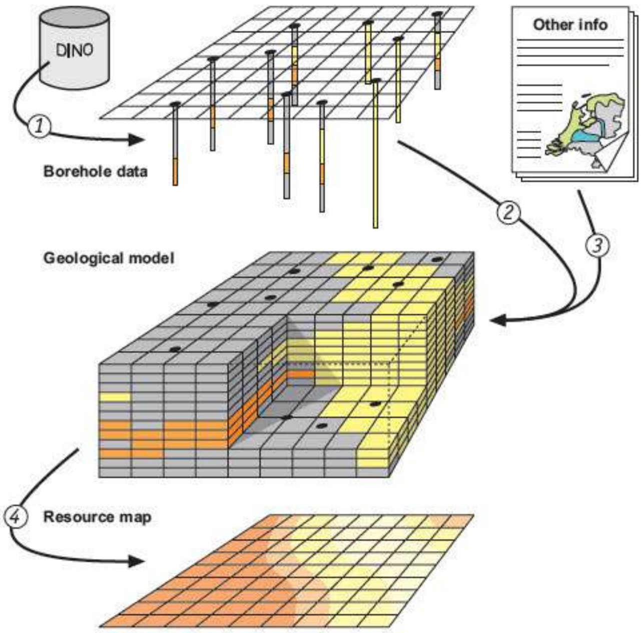


Fig. 5. Summary of the modelling procedure: 1. retrieval of borehole data from DINO, discretisation and upscaling on high- and low-resolution grids (see text for explanation); 2. interpolation of voxel attributes using linear kriging; 3. using formation-boundary surfaces as constraints. 4. Resource maps are generated according to user-defined criteria.

Exploitability practices and model dimensions

Clay is usually extracted using earth-moving equipment such as backhoes. With virtually no exception, dredging techniques are not used, as dewatering and regaining a more or less normal clay texture requires a lengthy ripening process. As the larger part of the country has a high groundwater table, most clay extractions are mere land-surface lowerings of 1 to 1.5 m (Fig. 6, left panel). Only on higher grounds in the eastern and southeastern parts of the country, clay is extracted from deeper quarries.

Fig. 6. Left panel: the extraction of clay using a backhoe, near the town of Arnhem (Fig. 2). Right panel: the extraction depth is about 1 m (including ~30 cm of overburden); relevant lithological variation on that vertical scale is clearly visible. A caliche-horizon within the oxidised clays (not visible on this scale) presents a challenge, as it has to be removed before continuing extraction. Photo: DM.

Backhoe operators visually select clay while extracting, using a set of rather subtle criteria that relate to the share of fines ('smoothness'), the iron content (colour), the presence of calcareous nodules and shells ('dragging striations'), etc. These properties reflect sedimentary and/or pedogenic processes, both of which introduce vertical lithological variation on the sub-metre scale (Fig. 6, right panel). Hence, the aggregates model, having a vertical resolution of 1 m, is not detailed enough for assessing clay resources. We have therefore built a lithological model of higher resolution down to 3 m below land surface, with voxel dimensions of 250 · 250 · 0.2 m. This depth range is covered by shallow hand-drillings (Fig. 3) that are usually well-described, in description intervals of centimetres to decimetres.

In the lowlands (corresponding approximately to the main Holocene areas in Fig. 2), a 3 m model comprises the unsaturated zone and, hence, exploitable clay resources. In the uplands, where the groundwater table is lower, deeper resources are in principle accessible. In order to account for this, a second reference surface was created by interpolating the Holocene surfaces of brook valleys, disregarding the positive topography of surrounding hills (Fig. 7). Additional model space was defined down to depths of this reference surface plus 3 m, and filled with voxels from the aggregates model, recalculated at a 250 · 250 · 1 m resolution. The maximum model depth is 50 m below the surface (Fig. 8a).

The model area extends from the Dutch state boundaries with Belgium and Germany to the shoreline of the North Sea. It includes the Wadden Sea and IJsselmeer lake, rivers and other inland water bodies, below which clay resources are considered inaccessible by definition. For model-consistency reasons, surface waters were not excluded from the model area. However, no effort has been put in dealing with peculiarities of the sub-aquatic domain, such as lower data-density and active sedimentation and erosion processes.

Interpolation procedures

The original aggregates model was interpolated relative to land surface. The high resolution model and the upgraded aggregates model were both interpolated relative to Dutch ordnance datum (NAP), for better reproduction of the mostly near-horizontal layer-cake stratigraphy of the Dutch upper Quaternary. A second improvement that was made is confining the interpolations by the formation-boundary surfaces of DGM, a national stacked 2D-grid model of the Dutch Quaternary and Tertiary (De Mulder et al., 2003; TNO, 2007b). This step was undertaken to avoid the correlation of lithologies that are adjacent but genetically unrelated. Visual inspection of the interpolation results showed that this step has significantly improved model consistency.

Clay quality attributes

In accordance with the approach to map deleterious impurities for ceramic clays, we added the occurrence of shell material and the extent to which sediment is peaty as quality attributes. In our dataset, these parameters are ideally given as abundance classes, which are semi-quantifications of visual observations. Keeping in mind the subjectivity of such classification, class 1 should be interpreted as rare ('single fragment', 'hardly observable', etc.), 2 as present ('common', 'clearly visible', etc.), and 3 as abundant ('above-average', 'omnipresent', etc.). Instead of, or in addition to lithological classification (Fig. 4, upper right panel), references to organic content may be included in descriptive text fields of our borelogs, e.g. 'rootlets' or 'plant debris'. Note that none of these attributes refer to the share of non-particulate organic carbon.

On the basis of the available information, a probability indicator for shell and peat admixture occurrence was defined and interpolated. It is set at 100% in case of abundance classes 2 and 3 or of unspecified admixture references, and at 60% in case of abundance class 1. The latter value has been chosen primarily for its effect on the interpolation results, which should reflect the characteristics of the underlying set of observations. A 60% attribute value produces a scattered signature if isolated, while it maintains spatial continuity in case of nearby observations of shell or peat material.

Calcareous nodules are not amongst the standard parameters in our borehole descriptions, nor do they seem to have been logged consistently in descriptive text fields. We therefore did not attempt to include them as quality attribute. As a pedogenic feature, calcareous nodules occur mainly around the water table that delimits clay extraction anyway. Hence, we feel that disregarding this phenomenon presents no serious limitation to the present large-scale resource assessment. Caution should be exercised, however, in case of known water-table lowering (e.g. polder-table adjustments), which may have put calcareous nodules in the unsaturated zone.

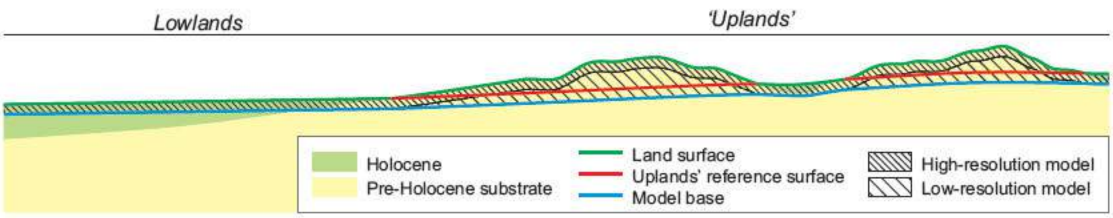
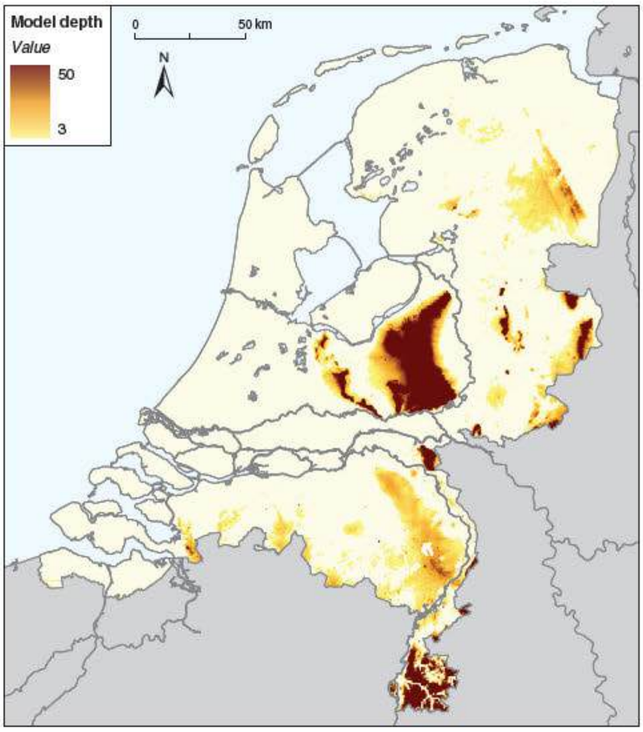


Fig. 7. Defining the model space for the clay-resource assessment (see text for explanation).



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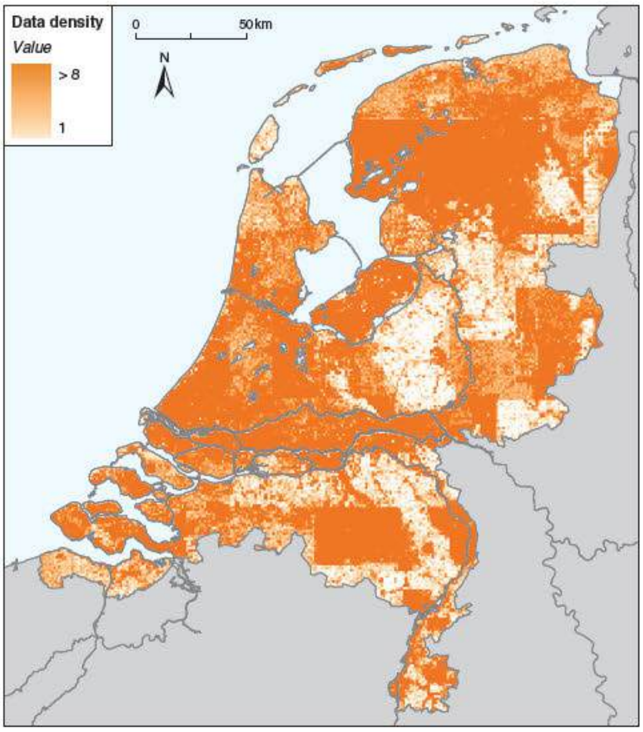
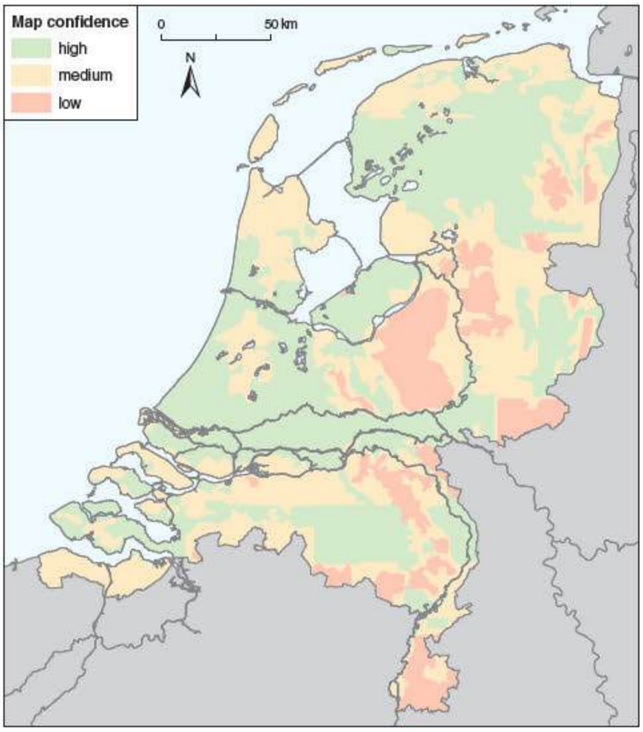


b.

Fig. 8. a. Model space dimensions (see also Fig. 7); b. the borehole density at the midplane of the model, as used for the map confidence classification (c; see text for further explanantion).



c.

Exploitability criteria

In principle, groundwater should be the first constraint to be used when assessing clay exploitability, for reasons outlined above. However, whereas the Geological Survey of the Netherlands manages a groundwater monitoring network with some 20,000 observation wells, it does not yet have national water-table grids available that can be inserted into our model. Instead of calculating exploitable clay reserves using groundwater data, we show cumulative volumes as function of hypothetical extraction depths. Other (non-hydrological) parameters that determine clay exploitability relate to lithology and resource architecture. Clay is considered exploitable unless:

- it is covered by ≥40 cm of peat. This criterion applies mainly to the lowlands, where peat is abundant, groundwater is high, and 40 cm would constitute a significant part of extractable volumes by definition.
- it is covered by >5 m of non-clay material (sand in most cases). This criterion applies only in the uplands, where the resource model covers thicknesses in excess of 5 m.
- the lithology is till (boulder clay), which was formed below the advancing Saalian ice sheet in the northern parts of the country. In our database, till classifies as loam or clay (in the latter case sometimes erroneously), and it is therefore included in the results of queries for the clayey lithologies that we use. However, we do not consider till a clay resource, even though it was in fact used historically, e.g. for the construction of the so-called 'Afsluitdijk' which separates the IJsselmeer lake from the Wadden Sea (Fig. 2; Van der Meulen et al., in press). The Saalian till is a stratigraphic unit in the official Dutch lithostratigraphic scheme (Drente Fm, Gieten Mbr; cf. De Mulder et al. 2003), so the combination of lithological and stratigraphic attributes allows for a proper identification of till in our model.

– it belongs to the uppermost soil. The sediment classification system used in our database does not systematically include pedogenic features, and a rooted sod or an otherwise organically enriched soil horizon may not have been described properly. Ideally, it would either classify as peat or have a peaty attribute. However, if the emphasis in the description was put on the unaltered lithologies, clay may appear in the topmost model layer, whereas it is in reality never suitable for any application. We therefore discarded the topmost 20 cm-layer of our model.

As a special resource category, the loess deposits of Limburg were included in the clay stocks as a labelled sub-volume. Being a stratigraphic unit (Boxtel Fm, Schimmert Mbr, cf. De Mulder et al., 2003), loess was identified in the same way as till.

Map confidence

Our results are based on a very large, heterogeneous dataset, which precludes a manual assessment of data quality. As a consequence, we have not been able to produce an adequate accuracy assessment as part of our modelling, which would have to involve not only the quality of the borehole data, but also that of the formation boundary surfaces that have been used. Instead, we present an *a posteriori* assessment of map confidence, relating to variation in data coverage and the extent to which the underlying model adequately reproduces known geological features (rather than artefacts).

A large part of the Dutch lowlands has been surveyed as part of the national 1 : 50,000 geological mapping program, which was terminated before completion in the 1990s. As a result, the shallow, high-resolution lithological model that has been constructed for these areas generally relies on densely spaced, high-quality survey boreholes. The opposite applies to the larger part of the uplands, where data is sparser and the model depth exceeds the average drilling depth. This variation is visible in Figure 8b, which shows data density at the midplane of the model space.

Recognisable geological features generally prevail over clear artefacts (bull's-eyes patterns etc.) in model results for areas having a midplane borehole-density of more than 5 per km^2. The opposite occurs where the density is less than 1 borehole per km^2. Areas with densities between 1 and 5 boreholes per km^2 constitute an intermediate category, where the extent to which geological features are resolved seems to depend mainly on the complexity of the area. On the basis of these general observations, a threefold map-confidence classification (high, medium, low) was defined and used as an overlay on result maps (Fig. 8c). Confidence strictly relates to the regional scale for which the result maps are intended to be used.

Results

Clay quantity

The total volume of clay in the model space is estimated at 47.7 km^3 (Fig. 9a), and 42.1 km^3 when disregarding sub-aquatic clays (not shown in the figure). The distribution of clay clearly fits the general geological layout of the Netherlands. It occurs mainly in the coastal provinces, except in the dune and beach areas where sand predominates, and along the main rivers in the central parts of the country. The resource model is also consistent with regional geological features, such as channel-belt architecture, and with the effect of historical peat extraction (Fig. 10).

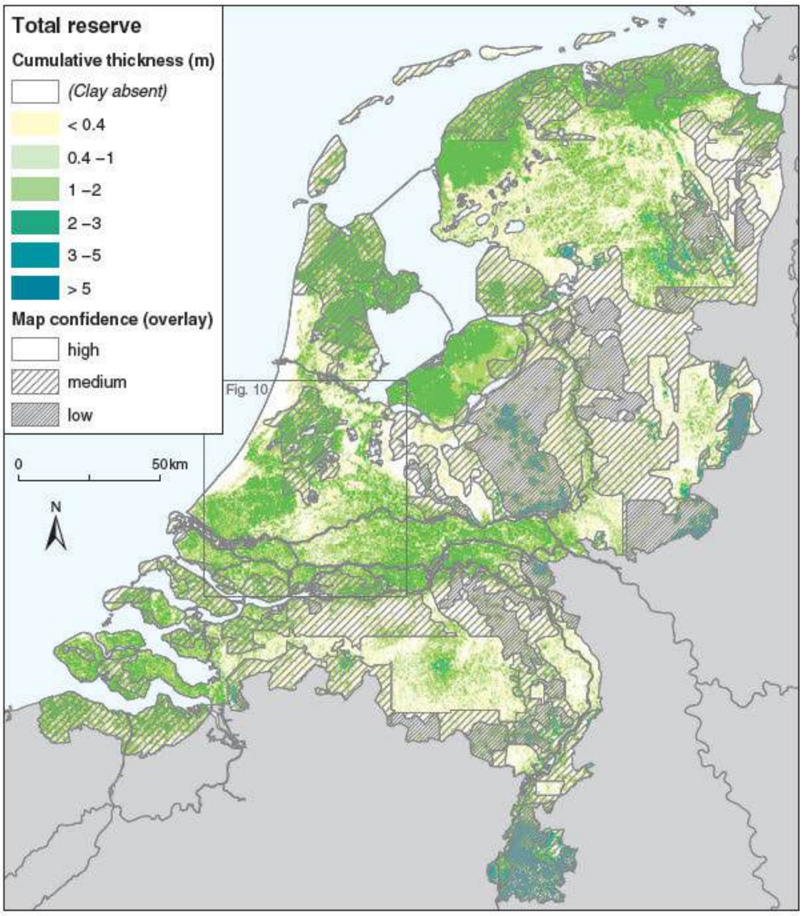
The geologically exploitable sub-volume, defined according to the above criteria but disregarding groundwater, is estimated at 34.7 km^3, i.e. 82% of the total volume (Fig. 9b). This includes clays having thicknesses that are insufficient for economically viable extraction. When disregarding, as an indication, clays of less than 40 cm in thickness (yellow in Fig. 9), the exploitable volume would be reduced by 1.4 km^3 (or 4%). However, just like other primarily economical factors, we disregard resource thickness in further calculations. The volume of loess in Limburg is estimated at 3.0 km^3, almost all exploitable. This amounts to 7.1 and 8.6% of the total and exploitable clay stocks, respectively.

We explored exploitability in relation to groundwater by calculating resource quantities down to an assumed groundwater table depth range. In the lowlands, we estimate it at 1 to 1.5 m below the surface, in accordance with common clay extraction depths in this type of area. The situation in the uplands is less straightforward, so we approximated exploitability by calculating resources with respect to both land surface and the aforementioned second reference surface (see Fig. 7). The average of these results, i.e. 12.3 to 18.0 ± 2.0 km^3 for the chosen depth range, is our best guess of the exploitable amounts of clay in the Netherlands (Fig. 11).

About 0.7 km^3 of clay is present on the embanked floodplains of the Rhine and Meuse, the 'classical' resource area for the structural-ceramics industry (see Fig. 2). Virtually all of this clay occurs in a top layer of 1 to 1.5 m that is unsaturated unless river discharges are high, so most of it is exploitable. Embanked-floodplain clays are currently at risk of being removed for river-widening purposes (Van der Meulen et al., 2006), without full consideration of their value as strategic resource.

Clay quality

Clay in the fine resource category (18.3 km^3, ~43% of the total reserve in the model volume for land areas) is limited to the fluvial plains and some landward parts of the coastal zone (Fig. 12a). Both near the coast and in the uplands, clay is



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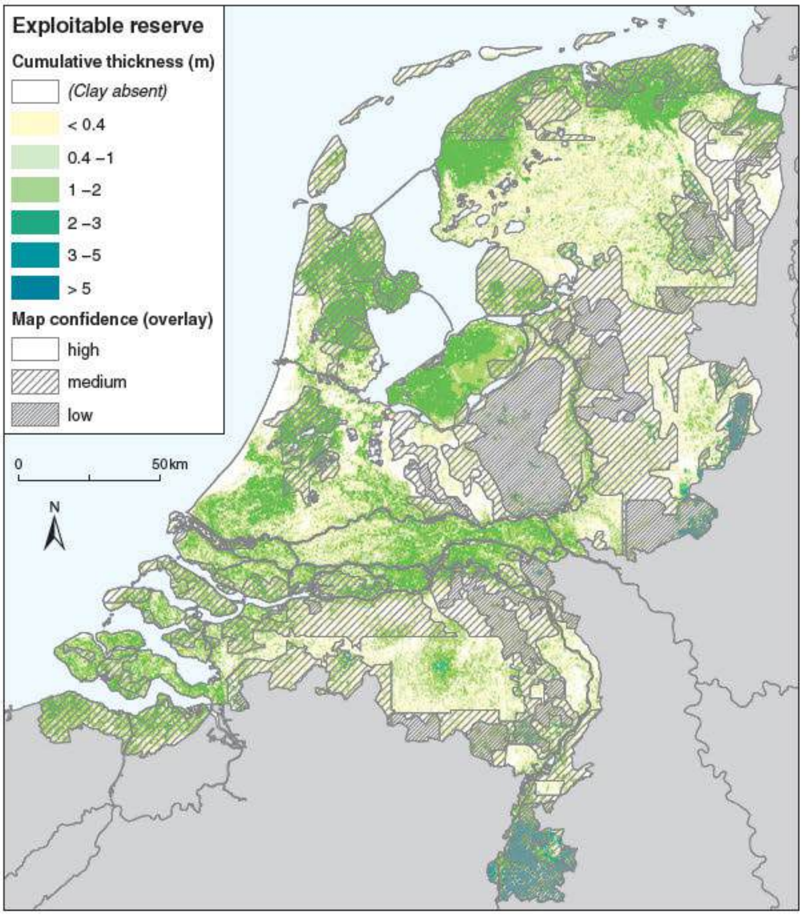


b.

Fig. 9. Clay-resource map of the Netherlands showing the total reserves within the model space (a), and the exploitable reserves (b) according to exploitability criteria explained in the text. For the definition of map confidence see Fig. 8.

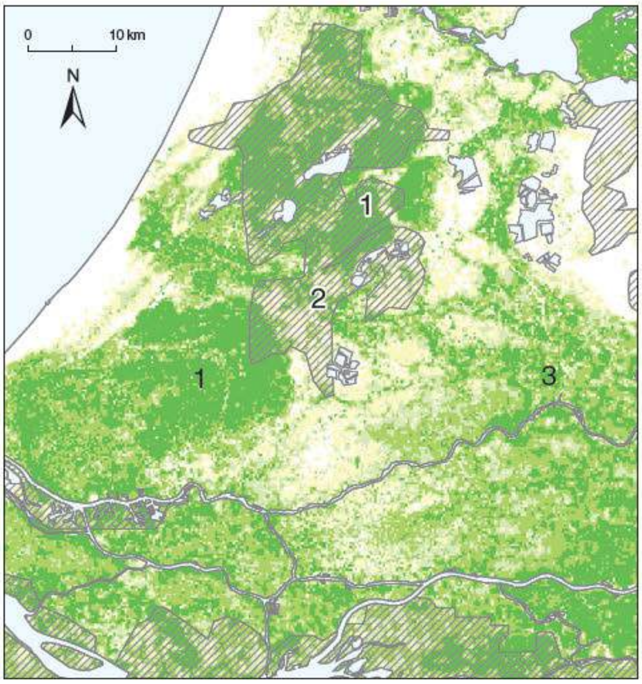


Fig. 10. Detail of the clay-resource maps of the Netherlands (see Fig. 9 for location and legend), showing a number of adequately reproduced geological features: 1. clay surfacing as a result of extraction of the overlying peat in mediaeval times; 2. the tract of a former Rhine distributary; 3. channel-belt architecture below the Rhine-Meuse river plain.

predominantly silty or sandy. As both the coarse and the fine resource categories have been used, historically and present (as can be inferred from Fig. 2), we did not attempt to interpret coarseness in terms of a limitation to applications.

As expected, consistently high shell-occurrence probabilities are limited to the coastal area (Fig. 12b). Within this domain, the highest values are observed in former peat extractions, where marine clays have been uncovered with higher shell contents than most of the superficial clays occurring elsewhere. Scattered higher shell probabilities in fluviatile and other terrestrial environments reflect observed occurrences of land molluscs, which are thin-shelled and less problematic to ceramic-product fabrication than marine shells. Organic debris occurs in a wider zone than shells; in fact, only till, loess and the clays in the upstream Rhine and Meuse areas have low abundances (Fig. 12c).

According to our data, and based on the joint probability of encountering shell or organic material, 32% of the exploitable clay (as shown in Fig. 9) would disqualify as ceramic material (Fig. 13). This is most probably an underestimate, as the chances that these admixtures are present but unaccounted for in borehole descriptions are bound to exceed those of the opposite situation. If we completely disregard areas where the probability of encountering deleterious impurities exceeds 25% or 10%, in order to explore the effect of this underestimation, 44 or 56% of the clay-resource would have to be discarded, respectively. It is recommended to interpreted Fig. 13 qualitatively, keeping underestimation in mind and focussing on the overall image. On that level, the map is consistent with the main ceramic-clay resource areas, which are situated in the upstream Dutch Meuse and Rhine rivers, easternmost Gelderland and Overijssel, and southern Limburg (Fig. 2).

Spatial limitations

5% of the geologically exploitable clay is situated below built-up areas, and 21% occurs below areas of the so-called Ecological Main Structure (*'Ecologische Hoofdstructuur'*, Anonymous, 2004; Fig. 13, inlay). Other than for aggregates, clay resources in the latter category should not be considered off limits by definition. Clay extraction is less controversial than most other forms of mineral extraction, given the small scale of most operations and the favourable conditions this presents for site remediation. Because of this, clay extraction is quite commonly coupled to nature development, ever since the WWF and the industry reached a co-operation agreement in 1994 (based on a plan presented by Helmer et al. 1992).

Beyond constraining extraction depths, groundwater may limit clay extraction in two types of situation. Where clay confines a shallow artesian aquifer, its (partial) removal may lead to seepage. Caution should be exercised, for example, in

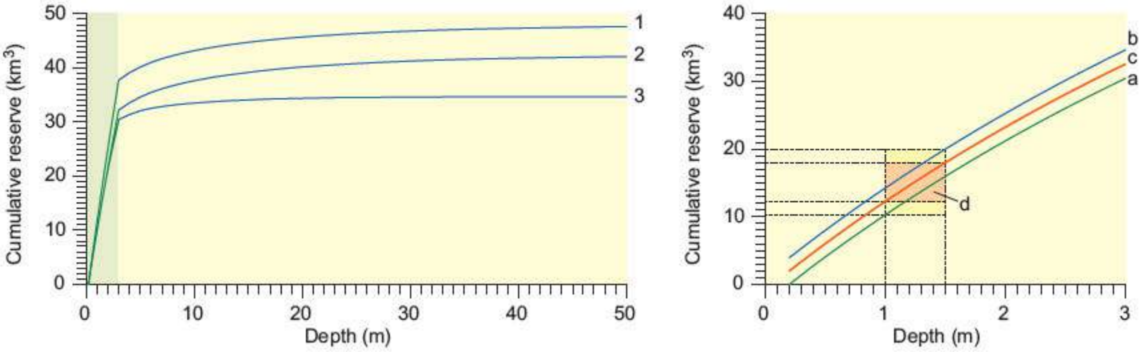
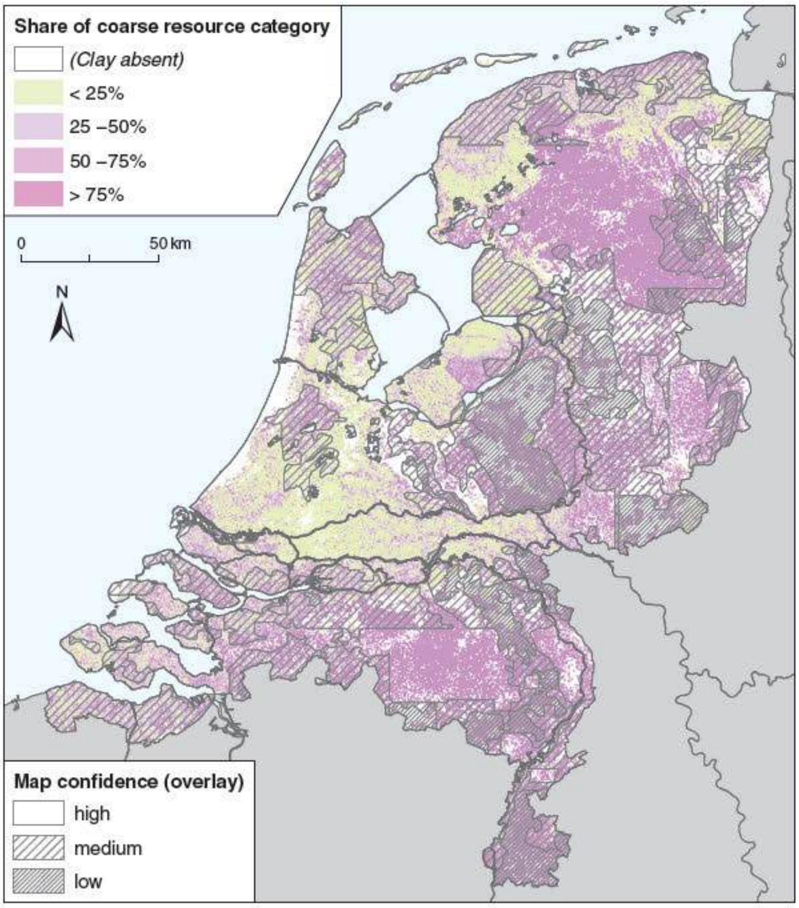
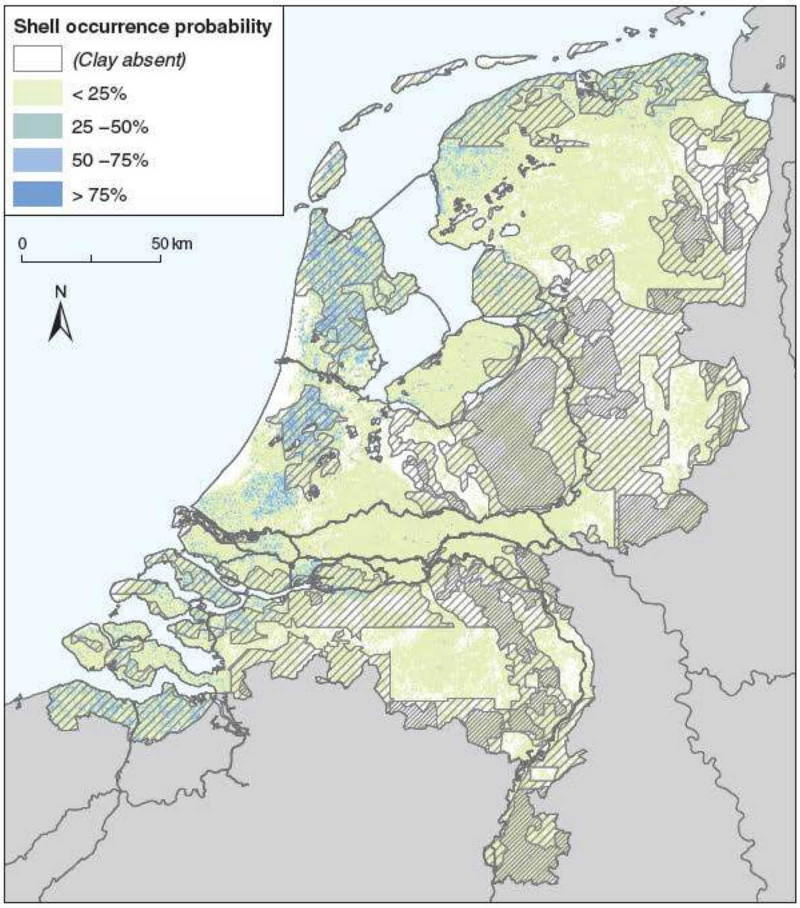


Fig. 11. Clay volumes as a function of depth. Left panel: green shading and lines are used for the vertical extent of the high-resolution model; yellow shading / blue lines for extent of the low-resolution model; 1. the total volume of clay in the model space; 2. idem, disregarding sub-aquatic occurrences; (3) the exploitable subvolume (disregarding groundwater). Right panel: a. exploitable volumes down to 3 m below the surface; b. idem, down to 3 m below the reference surface (see text and Fig. 7 for explanation); c. average of a and b; d. best guess of the exploitable clay volumes in the Netherlands.

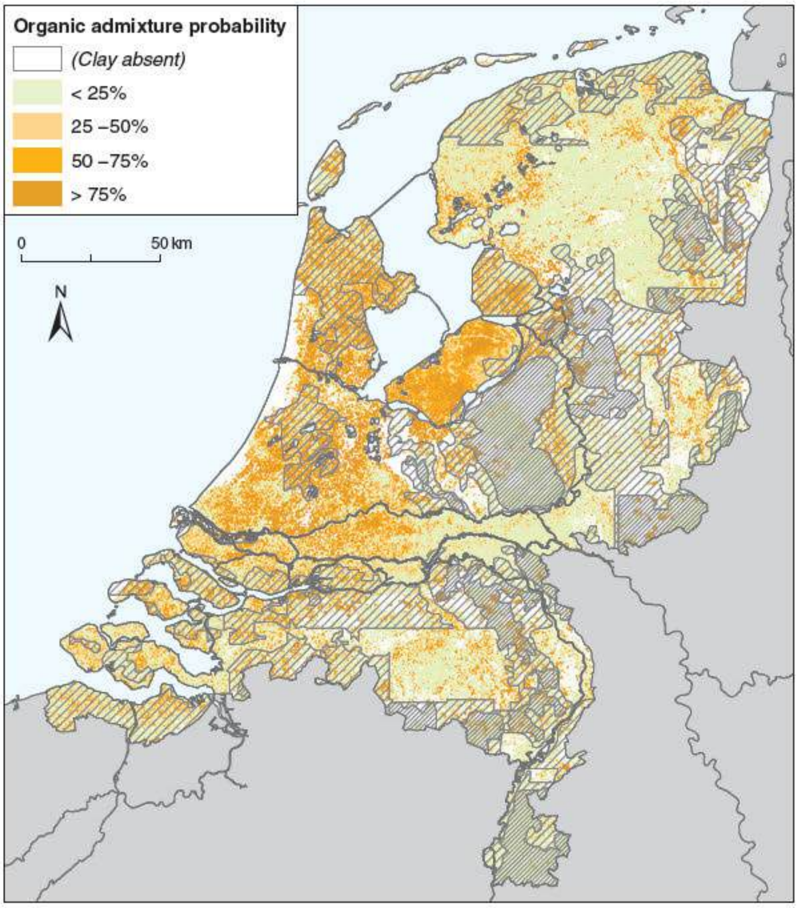


a.



b.

Fig. 12. Clay-quality maps showing the share of the coarse clay-resource category as explained in the text (a), and the occurrence probabilities for shell material (b) and peat or plant fragments (c; next page). All values apply to the entire clay volume in the model space (Fig. 9a). For the definition of map confidence see Fig. 8.



c. *Fig. 12. (continued)*

case of Holocene sandy channel-belt deposits overlain by floodplain fines in polder areas. A similar caveat applies to a peat-clay sequence on top of an artesian aquifer, in which case removal of clay may lead to heave and seepage. This problem applies, roughly, in and around the peaty zones in the coastal provinces (Fig. 2).

Concluding remarks

Clay occurs quite abundantly in the coastal zone and along the rivers Rhine and Meuse. Potential ceramic clays occur in the upstream parts of these rivers, and in the central-eastern-most parts of the country. This study has improved our appraisal of Dutch clay resources, and the results will be used to take the occurrence of clay into consideration in land-use planning. Most limitations of our modelling methods and yield calculations can and will be addressed when working on local scales, handling fewer data. Examples of this are the incorporation of groundwater data, and refined exploitability criteria, which can be tuned to local geological characteristics such as the sedimentary setting and pedogenic processes.

Exploitable clay volumes correspond to roughly 6000 annual consumption equivalents. Even when considering that the larger part of this amount is probably unsuitable for firing, this implies that clay is not a scarce resource and supplies should present no problem in the near future.

Disclaimer and acknowledgements

Although the authors adhere to its basic principles, this study does not formally comply with the Code for Reporting of Mineral Exploration Results, Mineral Resources and Mineral Reserves (Anonymous, 2001). In the terms of this code, our study would classify as a reconnaissance mineral resource, apt for mineral or spatial planning purposes by the government. Note that our results are not to be used for the purpose of (a) informing investors or potential investors and their advisers or (b) satisfying regulatory requirements.

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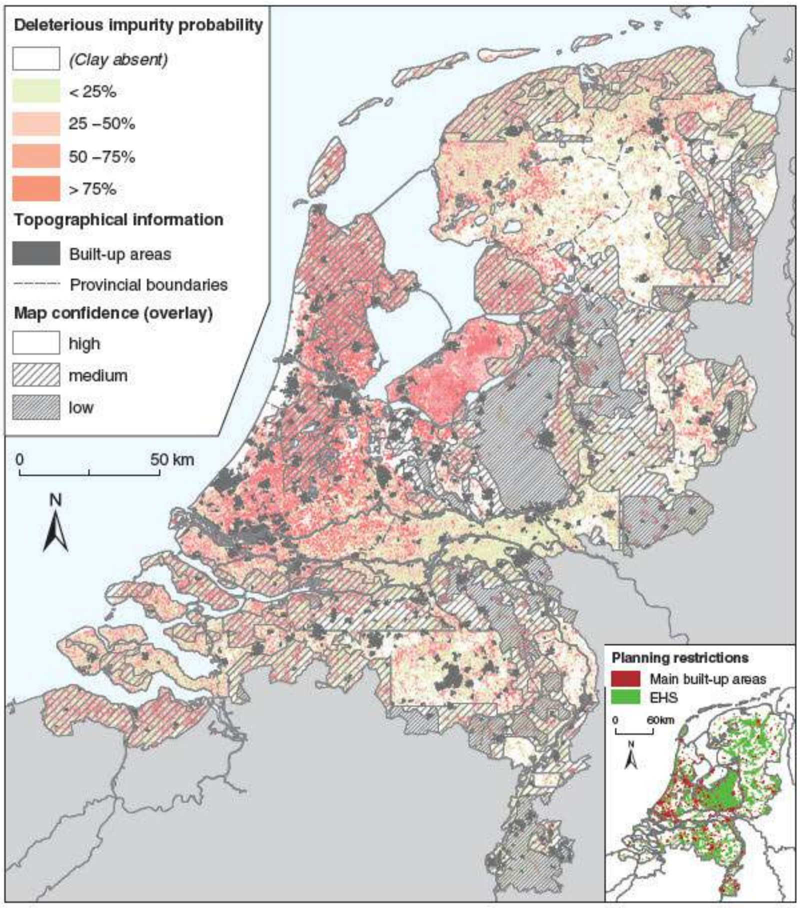

Fig. 13. The joint probability of encountering shell or organic material within the geologically exploitable stock (Fig. 9b). The inlay shows the Ecological Main Structure referred to in the text. For the definition of map confidence see Fig. 8.

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Bijlage 4 – Klei als hernieuwbare grondstof

Van der Meulen, M.J., Wiersma, A.P., Van der Perk, M., Middelkoop, H. Hobo, N., 2009. Sediment management and the renewability of floodplain clay for structural ceramics. Journal of Soils and Sediments 9: 627-639. doi:10.1007/s11368-009-0115-8

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Sediment management and the renewability of floodplain clay for structural ceramics

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Abstract

Background, aim, and scope The Netherlands has vast resources of clay that are exploited for the fabrication of structural ceramic products such as bricks and roof tiles. Most clay is extracted from the so-called embanked floodplains along the rivers Rhine and Meuse, areas that are flooded during high-discharge conditions. Riverside clay extraction is—at least in theory—compensated by deposition. Based on a sediment balance (deposition versus extraction), we explore the extent to which clay can be regarded as a renewable resource, with potential for sustainable use. Beyond that, we discuss the implications for river and sediment management, especially for the large engineering works that are to be undertaken to increase the discharge capacities of the Rhine and Meuse.

Materials and methods Extraction rates are based on production statistics for clay, as well as those for fired end-products. Deposition rates are estimated from published and unpublished geological data (clay volumes and thicknesses, datings, etc.) and from morphological modeling studies. Comparisons between extraction and deposition are made at three different time–space scales: (1) long term (post-1850)/large scale (all Dutch floodplains), (2) present/large scale, and (3) present/site scale. The year 1850 is relevant because it approximately marks the beginning of the current, fully engineered river systems, in which depositional processes are constrained by dikes and groynes. As the Industrial Revolution began in the same period, post-1850 sediments can be identified by their pollution with heavy metals.

Results (1) We estimate the post-1850 clay volume in situ at about 0.20 km^3, and the total extracted volume in the same period at about 0.17 km^3. This puts the net long-term average deposition rate of clay at ~1.3 million m^3/year and the corresponding extraction rate at ~1.1 million m^3/year. (2) Current accumulation is approximately 0.4 million m^3/year and expected to increase, and current extraction is about 0.7 million m^3/year and expected to decrease. (3) Clay extraction creates a depression that has an increased sediment-trapping efficiency. This local effect is not considered explicitly in large-scale morphological modeling. Based on maximum observed sedimentation rates, we estimate that replenishment of a clay site takes in the order of 150 years. As clay extraction lowers some 0.5 km^2 of floodplain yearly, a surface area of approximately 75 km^2 would be required for sustainable clay extraction. This is about 1/6 of the total surface area of the embanked floodplains.

Discussion On the long term, clay extraction from the embanked floodplain depositional environment has been sustainable. At strongly decreasing deposition rates, the ratio between extraction and replenishment seems to have shifted towards unsustainable. However, current sedimentation is estimated conservatively. The site-scale approach

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suggests that, even if extraction would currently exceed deposition, this could be resolved with sediment management, that is, with site restoration measures aimed at higher sediment-trapping efficiency. Our results have implications for river engineering, especially where substantial digging is involved (floodplain lowering, high-discharge bypass channels, obstacle removal). First, this inevitably affects the clay resources that we studied, while resource sterilization should be avoided. Secondly, the effect that any form of digging has on subsequent sedimentation—increased rates—relates to long-term river maintenance.

Conclusions, recommendations, and perspectives We conclude that floodplain clay is a renewable resource, especially if managed accordingly. Beyond that, we established that clay extraction is a significant, lasting factor in floodplain evolution along the Rhine and Meuse Rivers. The interests of the extractive industry and river managers could be served jointly with sediment management plans that are based on sediment-budget analyses.

Keywords Building raw materials · Clay · Netherlands · Renewable resources · Sediment management · Structural ceramics industry · Sustainable resource management

1 Background, aim, and scope

The Netherlands has vast resources of clay that are exploited for earthworks and fabrication of structural ceramic products such as bricks and roof tiles (van der Meulen et al. 2007a, b; Fig. 1). As water tables are generally shallow, most Dutch clay extractions are land-surface lowerings of about 1.5 m, with a surface area of a few hectares, the majority of which are located in the embanked floodplains of the rivers Rhine and Meuse. Such excavations are relatively easy to restore and, following an agreement in the early 1990s between the Royal Dutch Association of Brick Producers (KNB) and World Wildlife Fund for Nature, Dutch Branch (WWF-Netherlands), riverside clay extraction became consistently coupled with nature development (Helmer et al. 1992; Fig. 2). In this respect, the extraction of clay compares favorably with that of most other minerals worked in the Netherlands.

Apart from the site restoration possibilities, riverside clay extraction stands out because it is undertaken in an environment where the resource is actively deposited, and exploitation is compensated by replenishment—at least in theory. The purpose of the present paper is to explore the extent to which clay can be regarded as a renewable resource, with potential for sustainable use (sensu Brundtland 1987; for discussions on sustainable mineral development, see Wagner et al. 2004; van der Meulen 2005). In the strictest definition, renewable resources are either biotic or fluxes (wind, hydropower, solar energy, etc.). In a broader sense, however, it refers to any resource that can be used without depleting its stocks, and this definition includes sediments. Unlike quarries or aggregate pits, riverside clay excavations dating back to the 1950s or earlier are known to have been replenished by overbank deposition, and they are now ready for a second round of extraction (Sigmond et al. 2001). This indicates that exploitation of clay resources can be sustainable, provided that the overall rate of consumption and deposition is more or less in balance.

In this paper, we compare the deposition and exploitation of clay resources (sediment budgeting). Beyond that, we address the extent to which humans determine sedimentary processes at a fairly large scale, which, in its turn, translates to river and sediment management options for the Dutch Rhine and Meuse. We do not intend to present an in-depth analysis of Dutch embanked floodplains as depositional environment: we present first-order system characteristics based on a review of largely existing data.

2 Concepts

2.1 Renewability and clay deposition

Consumptive use of renewable resources is considered to be sustainable if it does not exceed replenishment. In the context of the present paper, we define replenishment as sedimentation of clay (1) deposited in a setting that allows for (later) extraction and (2) of (potentially) fireable quality (Table 1). These criteria exclude subaqueous clay occurrences, as clay is invariably extracted using dry techniques: it is excavated, not dredged. They also exclude clays deposited in (supra)tidal marshes or other coastal settings because of the likelihood of deleterious impurities such as shell fragments or particulate organic matter (van der Meulen et al. 2007b).

We therefore approximate replenishment with an estimate of clay accumulation in the only significant, active terrestrial depositional environment in the Netherlands, i.e., the aforementioned embanked floodplains. The remaining portion of the Dutch lowlands, where some 60 km^3 of clay was deposited during the Holocene, has become almost completely sediment-starved as a result of diking (van der Meulen et al. 2007c). We disregard clay deposition along brooks, etc.

The present study focuses on clay extraction for structural ceramics. It may seem arbitrary to exclude clay for other purposes from our analysis, i.e., for earthwork such as dike building or landfill covering. However, other than being displaced and shaped, clay is neither altered for such applications, nor is it really removed from its depositional environment. Consequently, we do not consid-

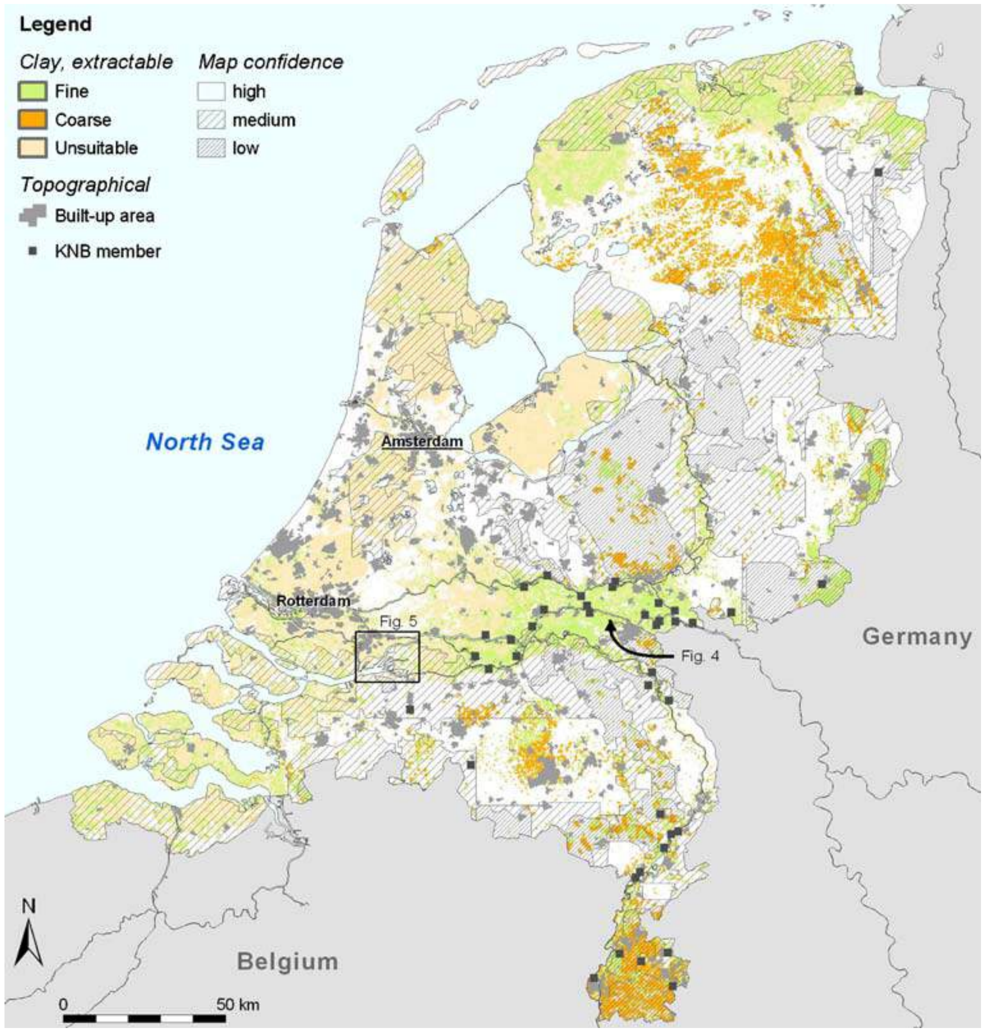

Fig. 1 Occurrences of clay in the Netherlands that are extractable, i.e., having (1) a thickness ≥1 m without intercalations and (2) <25% chance of encountering particulate organic material or shells. For details of the underlying resource assessment, see Van der Meulen et al. (2005, 2007b). *KNB*, the Royal Dutch Association of Brick Producers, represents the larger part of Dutch structural ceramics industry; *NB* plotted are brick production sites, not (necessarily) clay extraction sites

er this a matter of consumptive clay use and, hence, nor of resource depletion in the above sense.

2.2 Embanked floodplains: depositional system and processes

At present, Dutch rivers are confined to such an extent that they can hardly be considered rivers in the strict sense, i.e., hydraulically or sedimentologically (Figs. 3 and 4). The so-called winter dikes act as system boundaries: these are high dikes (up to ~5 m above the floodplain surface), placed at some distance from the river channel (up to ~500 m), in order to protect the coastal and fluvial lowlands against flooding during peak-discharge and/or storm-surge conditions. Embanked floodplains, i.e., the areas between the winter dike and the river channel, are flooded occasionally, typically between the late autumn and early spring. The so-called summer dikes, low dikes or strengthened natural levees that border the river channel, prevent the embanked floodplains from being flooded during summer (i.e., minor peak flow) conditions. Other than summer dikes, the river channel is fixated with groynes that concentrate flow in order to maintain channel depth for navigability. At few places, the riverbed is armored with concrete or armorstone.

Embanked floodplains are mostly pastures (see Fig. 4), a function that is compatible with occasional flooding during the winter season. In some areas, nature has been created (e.g., after clay extraction). Several brick and roof tile plants are present, built on flood-free mounds. Structural ceramics manufacture, including clay extraction, is the main industrial activity that takes place there. Some nineteenth century plants have protected heritage status.

Winter dikes were constructed between approximately 1000 and 1350 AD (Middelkoop 1997; Hesselink 2002). Groyne construction and river-bed armoring took place in the mid-nineteenth century, and during this operation ("river normalization"), meander bends were straightened as well. This suite of hydraulic-engineering measures is reflected in the depositional sequence of the embanked floodplains.

Prior to fixation, the river channel (or channels) migrated laterally within the confinement of the winter dikes, and

Fig. 2 A restored clay site along the river Waal. Extraction and landscaping are aimed at recreating the surface on which clay deposition took place, in this case the top of the underlying sandy channel deposits. In this way, a natural morphology is mimicked, which fits the amenity of this particular environment

sand and clay were both deposited and eroded throughout what later became embanked floodplains. After fixation in the nineteenth century, sand transport and sedimentation became almost exclusively limited to the river bed, typically in the form of migrating ripples and dunes. Only at high discharge, sand may be also washed onto the embanked floodplains, forming small natural levees on the channel banks. Clay and silt are carried in suspension and deposited on the embanked floodplains during and immediately after discharge peaks. Summer dikes prevent flooding (and sedimentation) up to certain discharge levels, but when overtopped, they are basically a sediment trap that retain floodwater with its sediment load. More importantly, river normalization raised the preservation potential of embanked floodplain clays because it puts an end to erosion of floodplain deposits by migrating channels. At present, a typical profile in the embanked floodplains consists of a clay layer of up to about 2 m in thickness, on top of sandy channel/point-bar deposits. This suite is obviously disturbed if aggregates or clay extraction has taken place.

The above depositional system description pertains to the Rhine and Meuse distributaries in the central Dutch fluvial plains, where most superficial clay extraction takes place. The situation along the upstream Meuse is different in the sense that the river is confined by the terraced flanks of an incised valley rather than by winter dikes. It is similar in having summer dikes, and the process of fines deposition behind these dikes is basically the same, even though the depositional surface is not a floodplain sensu stricto.

3 Materials and methods

3.1 Study area delimitation

We delimited our study area using the official positions of the state waters (which include the rivers Rhine and Meuse) and those of the primary flood defense systems (which includes the winter dikes). The combination of AHN, a high-density laser altimetry grid of the Netherlands, and satellite imagery allowed us (1) to verify and fine-tune the floodplain delimitations, (2) to exclude built-up/flood-free areas, and (3) if relevant, to exclude areas that seem morphologically or otherwise unsuitable for the deposition of clay with the desired quality. The most important exclusions occur in the Biesbosch, a semi-natural wetland area located at the apex of Hollands Diep, one of the Rhine–Meuse estuaries (Fig. 5). The morphology of the Biesbosch, with creek-like channels cutting through forested and reed-covered wetlands, resembles estuarine tidal flats, but estuary closure (the Delta Works) caused the former brackish mesotidal regime to shift to freshwater micro/non-tidal in 1970. In the absence of embankments and due to the vegetation, we do not expect clay of potential fireable quality to be deposited in this swampy area. All geographical information and altimetry data were courtesy of the Ministry of Transport, Public Works and Water Management.

Table 1 Approximate requirements for clay in the structural ceramics industry and for dike maintenance (for comparison)

Application	Share of grain-size fraction (%)					C-org (%)	$CaCO_3$ (%)
	<2µm	<10µm	63 250µm	≥250µm	Sand		
Roof tiles		50 57	< 20	< 40		<3	<25
Bricks		40 42	< 20	< 40		<3	<25
Extruded products		40 55	< 20	< 40		<3	<25
Dike maintenance	18 40				<40	<3	

All shares (percent) are given as mass percentages. Note that clay in the industrial definition may include lithologies that geologist would classify as loam or silt. Modified from Van der Zwan (1990)

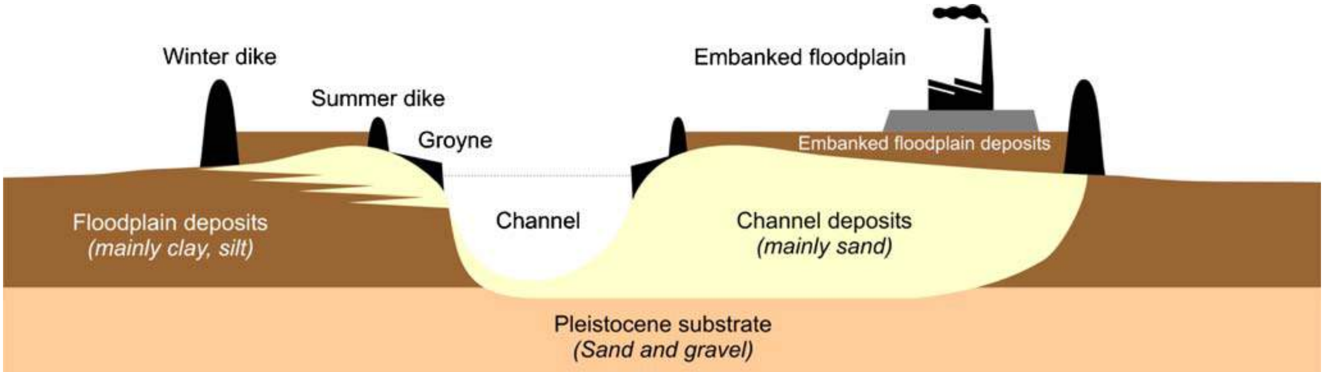

Fig. 3 Schematic cross section representing the embanked-floodplain depositional environment

3.2 Sediment-budgeting approach

We estimated and compared volumes of clay consumption at three different time–space scales (long term/large scale, present/large scale and present/site scale).

Long term/large scale Superficial clay occurrence in the embanked floodplains was assessed using a 3D clay resource model presented by van der Meulen et al. (2007b, see also van der Meulen et al. 2005). This geocellular model was obtained by a 3D interpolation of lithological composition (i.e., shares of clay, sand, gravel, etc.) and deleterious impurities such as shell fragments and organic debris, using about 380,000 borehole descriptions. Model raster dimensions are 250×250×0.2 m down to 3 m below the surface, and 250×250×1 m below that level. Using the criteria such as maximum overburden and intercalation thickness, technically exploitable clay volumes were identified by analyses of vertical model cell stacks. We clipped the results to the embanked floodplains in order to arrive at an estimate of the total exploitable clay resource volume in the study area. In order to be sure that no clay is included that has been removed, we clipped out the model below standing bodies of water in the floodplains (aggregates pits, etc.). Superficial clay can be assumed to have been removed at such places; this clipping step was taken to disregard data that predate extraction or earth removal. We then used new and published datings of clay deposits that allow an assessment of embanked floodplain accumulation rates over longer timescales (decadal to century scale) using heavy metal and radionuclide (^{137}Cs) distributions in soil profiles (see Middelkoop 2000; van den Berg and van Wijngaarden 2000).

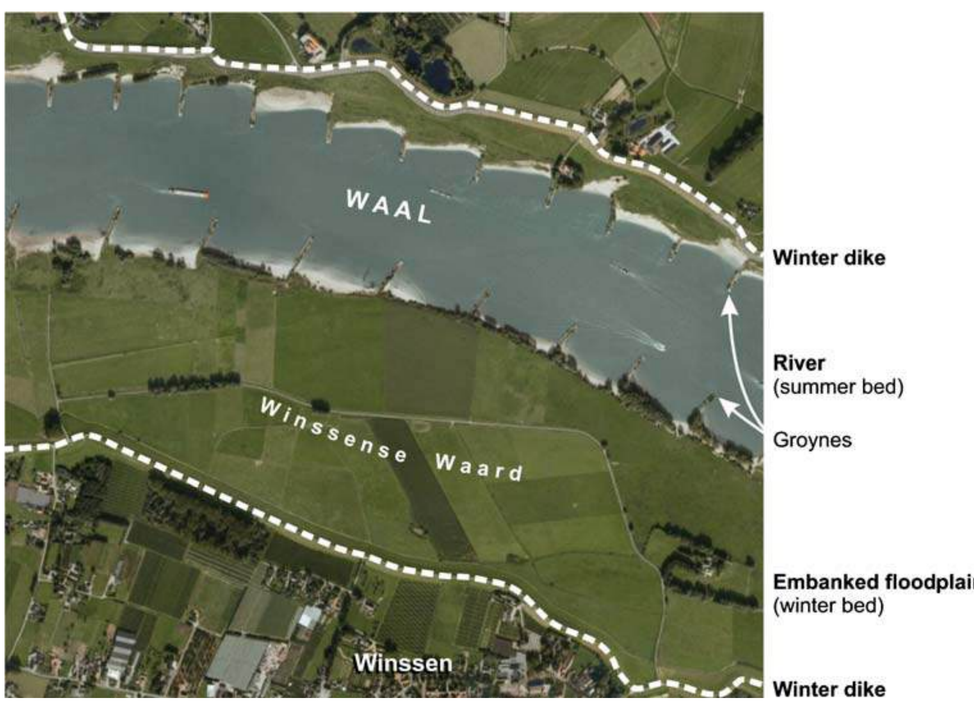

Fig. 4 Aerial photograph of the Winssense Waard, an embanked floodplain along the Waal distributary of the Rhine (see Fig. 1 for location)

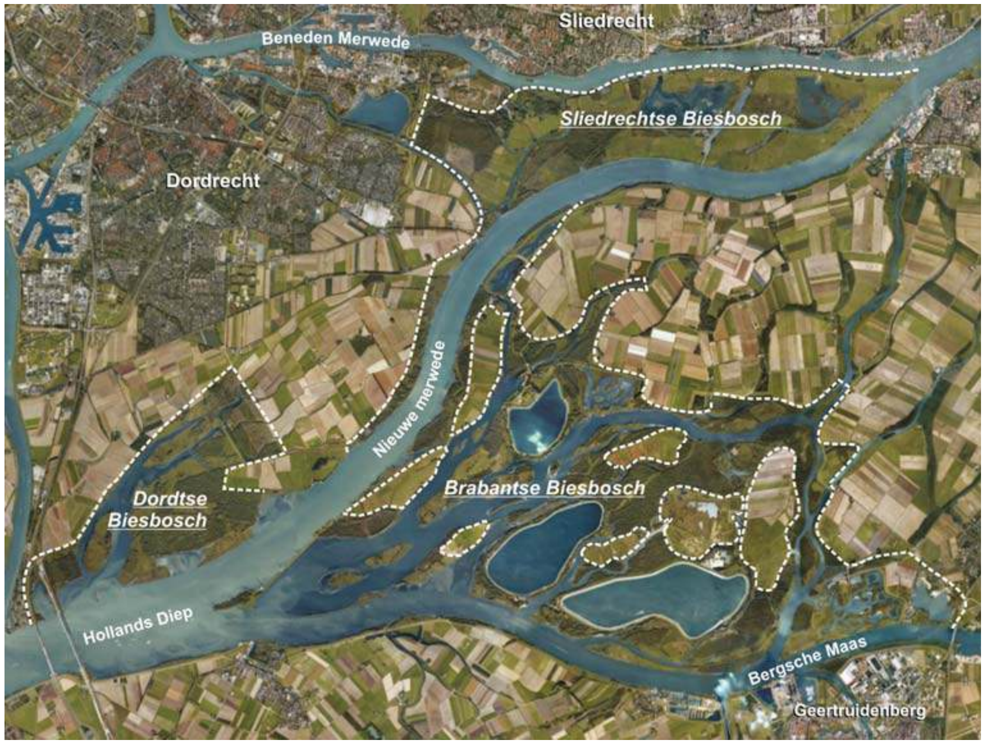

Fig. 5 Aerial photograph of the Biesbosch. *Canopied areas delimited by hashed white lines* have been excluded from our study area (see text for explanation and Fig. 1 for location)

Extracted amounts of clay are calculated or estimated from clay production statistics, gathered and published by the Dutch mineral-planning authorities, i.e., the Ministry of Transport, Public Works and Water Management (The Hague) for extraction in the so-called State Waters, and the Provinces in all other cases (see van der Meulen et al. 2007a for an overview). We also used brick and roof tile production statistics, gathered and published by Statistics Netherlands (Statline 2008).

Present/large scale The above approach has the advantage of robustness, as it is based on the entire clay volume in the embanked floodplains. However, it lacks precise time control and it reflects deposition processes and extraction practices that are not representative of the current situation. More specifically, sedimentation rates dropped due to increasing floodplain elevations and associated decreasing flooding frequencies (Middelkoop 1997), and the long-term average clay accumulation rate based on the entire clay volume is therefore an overestimation of current accumulation. A second-order approach to the evaluation of sustainable clay extraction is based on the comparison of current extraction and sedimentation.

For the main distributaries of the Rhine, we used estimates of contemporary sedimentation rates and patterns from model calculations (van der Perk et al. 2008; Straatsma et al. 2009). The model consists of a hydrodynamic component (WAQUA) that simulates the two-dimensional water-flow patterns, and a sedimentation component (SEDIFLUX) that simulates sediment transport and deposition (Middelkoop and van der Perk 1998). Along the Rhine, the discharge-frequency distribution for 1901 to 2000 was used in combination with a sediment rating curve from 1970 to 2006. Model parameter values for sediment-settling velocity (6.7×10^{-5} m/s) and critical bed-shear stress for sedimentation (2.0 N/m^2) were assigned based on previous modeling studies (Middelkoop and van der Perk 1998; Thonon et al. 2005). In our analysis, we only took into account floodplains delimited as described above, and we excluded grid cells where erosion is likely to take place, i.e., cells where the critical bed-shear stress is exceeded more than once a year (e.g., on the river side of the summer dikes). The simulated sedimentation rates in kilogram per square meter per year were converted to millimeter per year, assuming a dry bulk density of the sediment of 1,600 kg/m^3. We verified and supplemented modeling results with sedimentation measurements, obtained using sediment traps (Middelkoop and Asselman 1998; Thonon et al. 2007). For the River Meuse, no SEDIFLUX-modeling studies have been performed, and therefore, we upscaled the accumulation rates measured in three representative embanked floodplains from one major flood event derived from sediment traps (Middelkoop and Asselman 1998) into yearly average values by using flood-frequency statistics.

In the present/large-scale approach, we included deposition in water bodies that occur in the embanked floodplains. These include aggregate pits that, strictly spoken, do not meet the area delimitation criteria discussed in Section 3.1 because clay deposited at such depths (e.g., 20 m) cannot be considered a (future) clay resource. However, we could not systematically distinguish between such deep pits and shallow water or periodically inundated former clay sites. Clay deposited in the latter setting can in principle be excavated (rather than dredged) and would at least technically qualify as clay resource. The resource quality issues associated with such choices is discussed in Section 5.3.

Present/site scale The above two approaches result in approximations of the sediment-trapping efficiency of the embanked floodplain depositional system as a whole, on two time scales. While this provides insight in the main system characteristics, including the overall impact of clay extraction, both methods are insufficiently tuned to extraction as such. Extraction in the floodplains is basically a local perturbation of the depositional system, in the sense that a depression is created that potentially increases the local sediment-trapping efficiency. However, clay extraction is neither represented in sedimentation modeling, nor has it been taken into account explicitly when calculating floodplain sedimentation rates from measured data.

In a third order approach, we explore replenishment of individual clay extraction sites. If, for example, the flooding frequency of a site increases proportionally to surface level lowering, then we expect sedimentation to attain (or exceed) the late nineteenth century rates, or the high levels that are currently observed in depressions in the embanked floodplains. This applies especially when landscaping of a clay extraction site would be geared towards sediment trapping. This requires capturing and retaining sediment-bearing (flood) water which could, for example, be achieved with an open connection to the river at high discharge and/or semi-enclosure by a low quay. Without elaborating on the viability or technicalities of such measures, we explore the effect of locally increased sediment-trapping efficiency associated with clay extraction, assuming that sedimentation can be raised to the highest observed rates, current or historical.

Heavy metal and radionuclide (^{137}Cs) distributions in soil profiles allow an assessment of the decadal-scale variation in floodplain sedimentation from around 1850 to present (Middelkoop 2000; van den Berg and van Wijngaarden 2000). The maximum attainable rates were used to estimate the rate at which a clay site is or can be refilled. We used SEDIFLUX-modeled maxima for comparison.

4 Results

4.1 Long term/large scale

The total surface area of the embanked floodplains is 490.5 and 454.3 km^2 when excluding bodies of standing water. The total exploitable clay volume, obtained from the clay resource model, is estimated at 0.615 km^3 (Fig. 6). The average clay thickness of 1.35 m is in good accordance with the generic layout of the floodplain deposits described above. The aforementioned process of river normalization around 1850, i.e., the shift towards the present constrained depositional setting, coincided with the onset of the Industrial Revolution, which had a significant impact on water quality in the Rhine and Meuse catchments. Industrialization is reflected in floodplain deposits as high heavy metal concentrations (Pb, Zn, Cu, and Cd). Chemical analyses enabled Middelkoop (1997, 2000) to distinguish between pre- and post-normalization overbank deposits (non-polluted and polluted sediments, respectively). Based on the depth over which increased metal concentrations occur in floodplain profiles from several sites, we attribute one third of the floodplain clays, i.e., 0.2 km^3, to post-1850. This puts the average net accumulation rate from 1850 to present at 1.3 million m^3/year, and the net pre-1850 rate (0.41 km^3 in 500 to 850 years) at 0.5 to 0.8 million m^3/year.

Just as the pre-1850 clay volume is determined by deposition and erosion, net post-1850 accumulation is the sum of deposition and extraction. In the absence of proper statistics, however, the latter factor can only be approximated. As reliable clay production figures date back to 1980 only, we estimate the order of magnitude using production statistics of bricks and roof tiles, which are available for 1938 to 1991 (Statline 2008). For this purpose (Fig. 7), we added (1) the cumulative brick volume (104×10^9 pieces, reportedly of the standard "*Waal Formaat*" size of $20\times7\times5$ cm) and (2) the cumulative roof tiles volume (3.69×10^9 pieces, at an assumed standard weight of 3 kg and a density of 1,700 kg/m^3). A comparison of the volume thus obtained with clay extraction statistics between 1980 and 1991 shows that consumption-based figures are underestimations of between 51% and 69%. An average coverage of 60% is used to arrive at extraction estimates from 1937 until 1979, yielding a total of 148 million m^3.

We obtained an estimate for the production from 1850 to 1936 assuming proportionality between clay extraction and economic growth (gross domestic product—GDP). From the 1950s till the early 1970s, clay production increased by about 2%/year, while GDP grew by 5.07%/year (van Zanden 1997). Applying this ratio to GDP growth for 1850 to 1937 (van Zanden 1997), we estimate an overall clay production increase from 0.8 to about 2 million m^3/year for this period, at an average increment of about 1%/year. Adding the cumulative annual totals for 1850 to 1937 to post-1938 production gives a crude estimate of 260 million m^3 of clay from 1850 to date. Sigmond et al. (2001) established that about two thirds of Dutch clay extraction takes place in the embanked floodplains. In the absence of a better figure, and after discussion with industry representa-

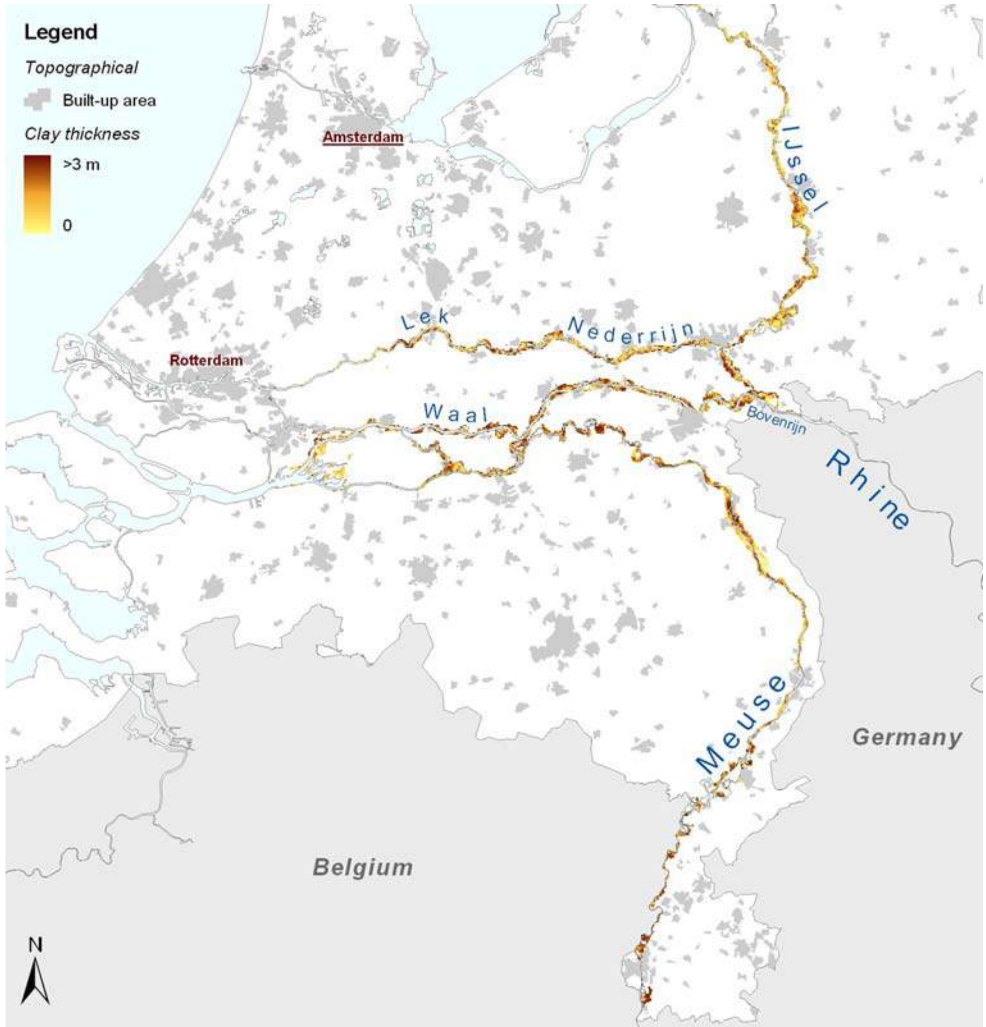

Fig. 6 Clay thickness in the embanked floodplains along the Rhine branches (names indicated) and the lower Meuse, and on the lowest terraces of the upstream Meuse (modified from Van der Meulen et al. 2007b)

tives, we extended this ratio to the past. This puts our estimate of total clay extraction from the embanked floodplains at about 170 million m^3 and the average rate of extraction at 1.1 million m^3/year. Post-1850 extraction is bound to have included a share of pre-1850 clays. As this share is unknown, gross post-1850 deposition cannot be determined. It is probably in the order of tens of millions of cubic meter in addition to the net value of 0.2 km^3.

4.2 Current/large scale

SEDIFLUX modeling of sedimentation along the Rhine distributaries results in a yearly deposited clay volume of $229 \times 10^3 m^3$ (Table 2, Fig. 8). This is in accordance with estimates obtained from sediment traps (e.g., Middelkoop 1997; Middelkoop and Asselman 1998). For the Meuse, the sediment trap data analysis puts the average accumulation along the Meuse at 0.85 mm/year (see Table 2), which corresponds to a yearly deposited clay volume of $190 \times 10^3 m^3$/year. We are aware of the limitations of upscaling local values to a complete river branch, but as far we know, these are the only published contemporary accumulation estimates for this particular river. Furthermore, the average accumulation fits well with the estimated accumulation rates estimated along the River Rhine from modeling studies. The combined yearly depositional volume for the Rhine and Meuse floodplains is $419 \times 10^3 m^3$. This corresponds to an average sediment accumulation rate of about 0.85 mm/year.

Minerals statistics for 1980–2006 show an overall decline of the extraction of clay for structural ceramics (Fig. 9). This trend was caused by changes in building practices. Up till the 1970s, most Dutch houses were built as brick constructions but since then, masonry became limited to the outer cavity leafs of external walls (as a facade): this basically substituted aggregates for clay as building raw material. On the decadal scale, production and consumption show a dependency on economy as evidenced, e.g., by dips during the recessions of the mid-1980s and early 2000s. KNB forecasts a further decrease in the years to come. In view of these trends, we base an estimate of current structural ceramic clay consumption on

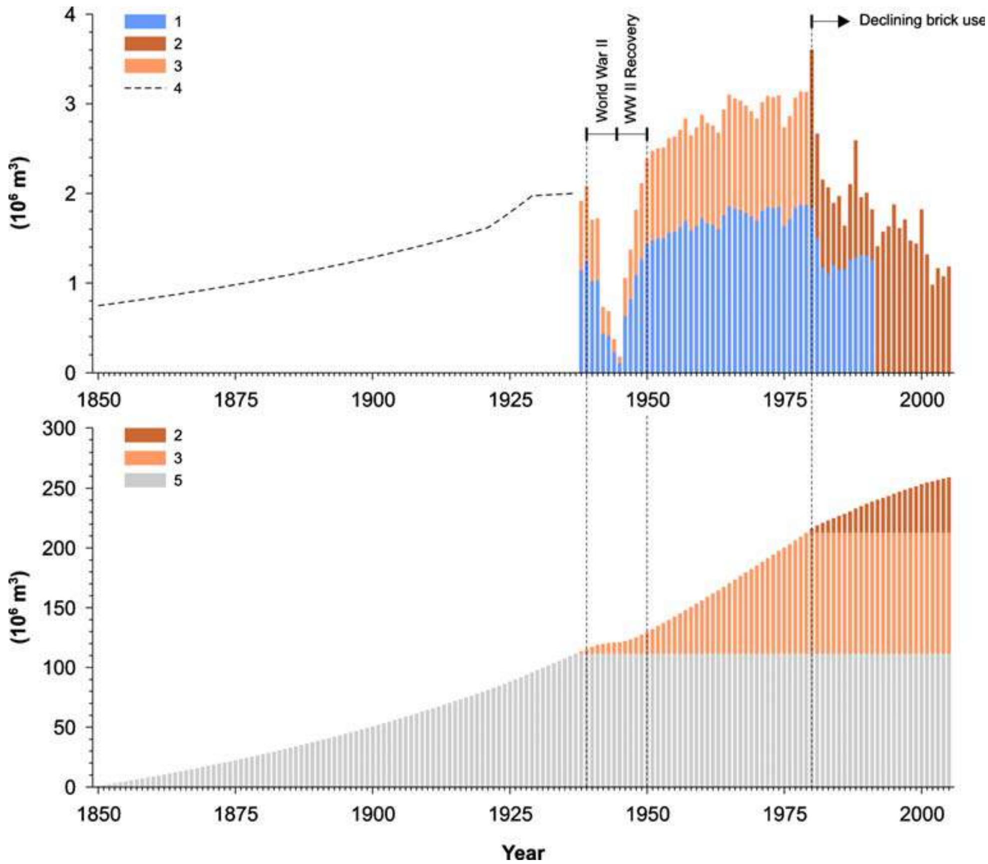

Fig. 7 *Upper panel* Annual clay extraction from 1850 to 2005: *1* clay required for recorded brick production from 1938 to 1991; *2* clay extraction statistics (1980 2006; further detailed in Fig. 9); *3* an estimate of total clay production based on *1* and *2*, see text for explanation; *4* estimated retrospective clay production (see text for explanation). *Lower panel* Cumulative clay extraction volumes from 1850 to 2006: *2*, *3*, *5* the cumulative volumes corresponding to *2*, *3*, and *4* in the *upper panel*, respectively

the figure for 2001 to 2006. The average production in that period was 1.1±0.1 million m^3. The aforementioned two thirds of floodplain clay in the total supplies (Sigmond et al. 2001) puts the estimate of embanked floodplain clay extraction at 0.7 million m^3/year. A query among the largest brick producers in the Netherlands, conducted for verification purposes, yielded a production estimate of 1 to 1.5 million m^3/year. We attribute this figure being higher to the fact that not all of the producers could distinguish between embanked floodplain clays and fluvial clays in general.

4.3 Current/site scale

Based on radionuclide data, maximum sedimentation rates observed in floodplain depressions range from 6 to 18 mm/year (Middelkoop 2000; van den Berg and van Wijngaarden 2000; Table 3). Maximum rates obtained in SEDIFLUX models of the Rhine floodplains are about 9 mm/year (see Table 3; van der Perk et al. 2008; Straatsma et al. 2009). Based on these data, we assume that surface level lowering and/or increased sediment-trapping efficiency have the potential to raise sedimentation rates to about 1 cm/year locally. Extracting 0.7 million m^3 of clay per year, from pits of 1.5 m in depth, requires the lowering of 0.5 km^2 of floodplain surface area per year. At a sedimentation rate of 1 cm/year, replenishment will take about 150 years. This implies that about 75 km^2 of floodplain would be required for sustainable clay extraction. This corresponds to about one sixth of the total floodplain surface area, which would suggest that sustainable clay extraction is indeed feasible. These values would be significantly lower if the observed shorter replenishment period of five to six decades (see above) is representative. There is, however, only one report of this phenomenon, and there are no verifiable sedimentation rates available at the appropriate time and spatial scales (decades and site, respectively).

5 Analysis and discussion

5.1 Is clay a renewable resource?

Our sediment budgeting effort allows for the following inferences:

- When considered on the long term (150 years), clay extraction from the embanked floodplain depositional environment has been sustainable. Cumulative resource depletion since 1850 (~170 million m^3) amounted to less than the volume of clay that we estimate remained from the same period. The volume estimates in our

Table 2 Current sedimentation rates for the Rhine distributaries (using the SEDIFLUX model) and for the Meuse (sediment trap data from Middelkoop and Asselman 1998)

River/distributary	Embanked floodplain surface area (km^2)	Average accumulation rate (mm/year)	Overall sedimentation rate ($10^3 m^3$/year)
Meuse	223.5	0.85	190.0
Waal and Bovenrijn	91.5	1.21	110.7
Nederrijn-Lek	82.2	0.82	67.4
IJssel	93.3	0.54	50.4
Total/average	490.5	0.85	418.5

See Fig. 6 for river and distributary names

balance are crude, especially that of cumulative clay use. Irrespective of that, data do allow us to establish that the clay resource volume increased while it was exploited, which would make clay a renewable resource by any definition, at least on this particular timescale and in this particular setting.

- The current balance (deposition ~0.4 million m^3/year; extraction ~0.7 million m^3/year) seems to have shifted towards unsustainable. However, our figure for current deposition is probably an underestimate, as the morphological consequences of clay extraction are not fully represented in the underlying modeling. In addition to that, the sediment-trapping efficiency of individual clay extractions, which is not among the current objectives for site restoration, can be raised significantly. If sediment accumulation rates at clay sites can (be made to) attain the maximum of ~1 cm/year, as currently and

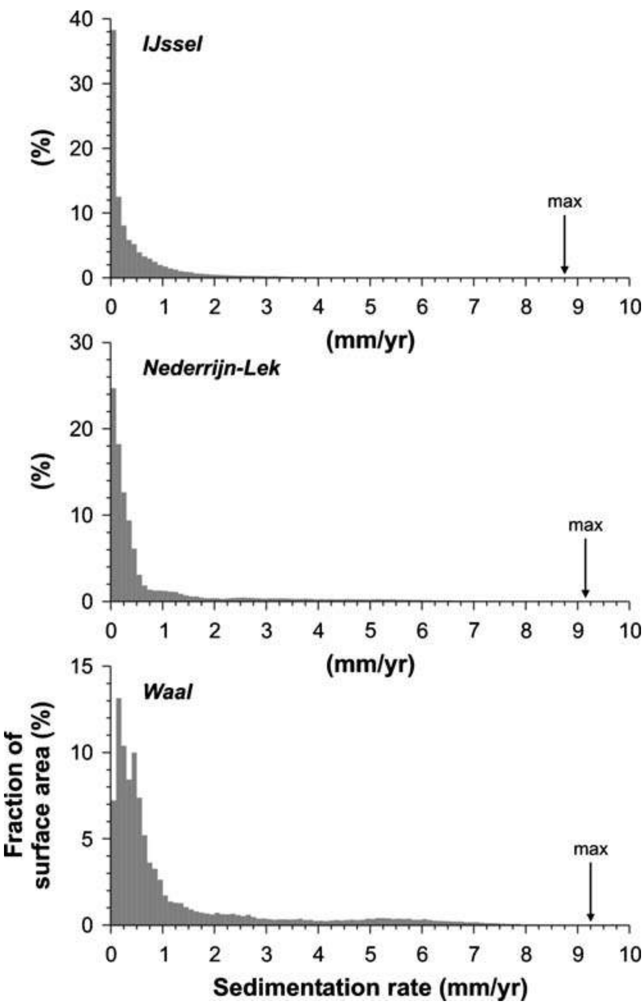

Fig. 8 Histograms of sedimentation rates modeled in the floodplains of the Rhine distributaries, expressed as cumulative share of the floodplain surface area (percent) per accumulation rate class (0.1 mm). Average and maximum values (the latter indicated with an *arrow*) are listed in Table 3

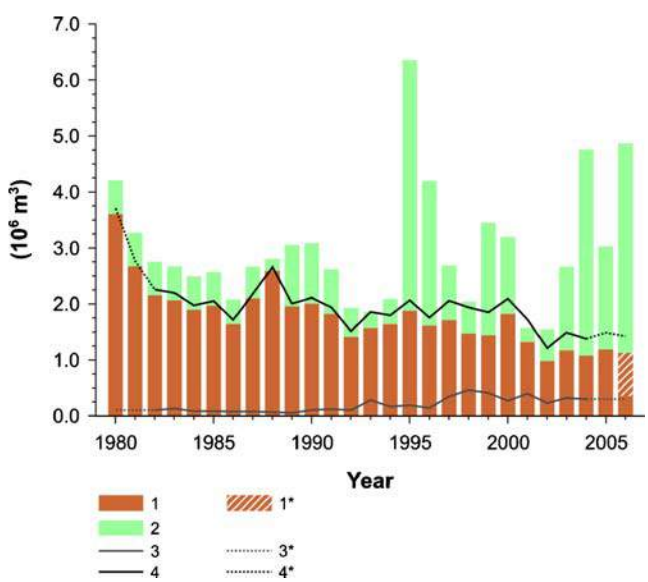

Fig. 9 Dutch clay production (1980 2006) for (*1*) structural ceramics (corresponds to *2* in Fig. 7) and (*2*) earthworks. Extraction for structural ceramics declines (see text) while net imports (*3*) rise somewhat. Consumption for structural ceramics manufacture (*4*) is approximated with *1+3*. Hatching (*1**) represents an estimate that corrects for unreported production in one of the provinces in 2006; dotting (*3**, *4**) indicates estimated values for *3* and *4*. Data: Van der Meulen et al. (2007a) and unpublished statistics from the mineral planning authorities (Provinces)

Table 3 Maximum sedimentation rates as derived from geological/historical reconstructions and obtained from modeling

River/ distributary	Embanked floodplain surface area (km^2)	Maximum average accumulation rate (mm/year)[a]	Modeled maximum accumulation rate (mm/year)[b]
Meuse	223.5	12	NA
Waal and Bovenrijn	91.5	18	9
Nederrijn-Lek	82.2	6	9
IJssel	93.3	6	9
Total/average	490.5	11	9

See Fig. 6 for river and distributary names

[a] Geological/historical reconstructions (see text)

[b] Obtained from modeling (see text and Fig. 9)

NA not available

historically observed in low-lying floodplain sections, then about one sixth of the embanked floodplain area would suffice for sustainable clay extraction. Based on this, we suggest that resource replenishment at the site level is a key objective for any future study into the renewability of clay. This applies to measurements of accumulation, as well as to the design of sediment traps.

Altogether, we argue that clay has been, probably is, and certainly can be managed as a renewable mineral resource. In that sense, the favorable comparison with other minerals worked in the Netherlands stands. A sediment-budget estimate for the Rhine reveals, for instance, that there is no net accumulation of sand and gravel in this system (Ten Brinke 2005), while the Dutch aggregates stocks are depleted at a rate of tens of millions of cubic meter per year (van der Meulen et al. 2005, 2007a). In fact, the amount of aggregate that is shipped towards the Netherlands over the Rhine (10–13 million m^3/year; van der Meulen et al. 2003) exceeds the amount of aggregate carried into the country by the same river system (0.6 million m^3/year; Kleinhans 2002) by more than an order of magnitude. Dutch resources of chalk (a Cretaceous carbonate resource) and silica sand (a Mio-Pliocene quartz resource) are obviously not replenished at all. The only other mineral resource of which extraction and replenishment are in balance is shell valves.

5.2 Analog: shell valves as renewable mineral resource

Mollusk shell valves, especially from cockle (*Cerastoderma edule*), are used in applications such as path pavements, drains, animal fodder and thermal and moist isolation (van der Meulen 2004; van der Meulen et al. 2007a). Shells are obviously a renewable mineral resource and their extraction in the Netherlands is managed accordingly. The annually permitted volumes are limited to the average yearly growth increment of the exploitable shell stocks, which is derived periodically from biological shell production (cf. Beukema and Cadée 1999).

In the present context, it is of interest that shell extraction is not a matter of harvesting living material, but of dredging fossil shell-bearing deposits: either Holocene tidal channel deposits in the Waddenzee, where the extraction quota is set at 210,000 m^3/year, or Quaternary marine deposits of the Westerschelde estuary and its prodelta, where the quota is set at 80,000 m^3/year. As it is a sedimentary system rather than an ecosystem that is exploited, shell resources and their management bear relevance to our discussion on the renewability of clay deposits. Points of comparison are:

- Depletion and replenishment are defined and quantified on the scale of the depositional system that is exploited, rather than of a single deposit.
- Resource management is ultimately based on bulk deposition rates, which are periodically updated.

5.3 Quality versus quantity

In our assessment of sustainable clay extraction, we primarily took a quantitative, volumetric approach: clay quality is only addressed, to some extent, in our area selection criteria. These criteria were based on the facts that fireable clay is known to have been deposited on grass-covered floodplains, that peat formation is inhibitive, etc. However, it is not known how relevant quality parameters relate to a concept of clay site replenishment, especially if natural site restoration is undertaken, with different vegetation, and possibly wetter conditions (for a bio-geochemical discussion of such areas, see Beumer 2009).

Modern production efficiency and quality requirements made the industry evermore “choosy” when it comes to their clay resources. Accordingly, assessing the quality of clay as ceramic material has come to be a rather specialized undertaking (e.g., van der Zwan 1990; van Wijck 1997), beyond the scope of the present study. On the other hand, successful experiments have been conducted to produce bricks from polluted dredging spoil (Claassen and van der Kooij 2003), and the structural ceramics industry historically worked clays with a much wider range of properties (textural, mineralogical, chemical; van der Meulen et al. 2007b). This suggests that there are possibilities beyond currently used clay resources, but we refrain from speculating on the quality aspects of sustainable clay resource management and suggest it is an important topic for future research.

The fact that post-1850 clays can be identified by their pollution state raises another quality issue. While heavy metal pollution may inhibit their use in earthwork, firing immobilizes these contaminants to such an extent, that even the aforementioned experimental dredging-spoil bricks pass the mandatory leaching tests for stony building materials (Claassen and van der Kooij 2003; Anonymous 2007). Furthermore, the water quality of the Rhine and Meuse improved significantly since the early 1980s, and the heavy metal concentrations in the floodplain clays of that period decreased accordingly (Middelkoop 2000). This implies that using evermore recent clay for structural ceramics, which is implicit to the renewability concept, should not present a problem from an environmental point of view.

6 Conclusions, recommendations, and perspectives

We conclude that floodplain clay is a renewable resource, if managed accordingly. Other than for shell material, it is recommended that management should arrange for resource replenishment, instead of regulating resource exploitation (with quota). Whereas biological shell valve production is a given fact, than can be monitored but not influenced, clay deposition is severely affected by the morphology and layout of a depositional environment that is largely artificial. We demonstrated that the depositional system has sufficient carrying capacity: enough clay is or can be trapped to exploit sustainably. Further research is necessary, however, to evaluate the clay quality aspects of such concept.

Clay extraction is one of the main influences on the sediment budget of the embanked floodplains of the Netherlands: humans appear to operate on more or less geological scales. Other than for the resource management issue at hand, such notion is important in the wider context of river management. Both Rhine and Meuse are awaiting substantial landscaping and engineering works, aimed at increasing discharge capacity (Silva and Kok 1996; van der Meulen et al. 2006). Individual measures range from the removal of hydraulic obstacles such as groynes, to land-surface lowering or digging high-discharge channels in the embanked floodplains. The latter category, i.e., anything that involves significant digging: (1) affects the same deposits that are a resource to the structural ceramics industry, while resource sterilization should be avoided; and (2) is expected to result in higher sedimentation rates, just as clay extraction does locally.

Hence, we propose that the interests of the extractive industry and river managers could be served jointly with river management approaches that are based on sediment-budget analyses. The more general inference is that managing rivers is just as much a matter of sediment management as it is of water management (cf. Brils 2002; Brils and De Deckere 2003; Owens 2005).

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Disclaimer Although the authors adhere to its basic principles, clay resource data presented in this study do not formally comply with the Code for Reporting of Mineral Exploration Results, Mineral Resources and Mineral Reserves (Anonymous 2001). Our results are not to be used for the purpose of (a) informing investors or potential investors and their advisers or (b) satisfying regulatory requirements.

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Bijlage 5 – Voorkomen zilverzand

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Silica sand resources in the Netherlands

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Abstract

Silica sand, (almost) pure quartz sand, is a valuable and scarce mineral resource within the shallow Dutch subsurface. High-grade deposits are exploited in the southeasternmost part of the country, as raw material for the glass, ceramic, chemical and other process industries. Dutch land-use policy requires that scarce mineral resources (including silica sand) are taken into consideration in spatial planning and when preparing for large-scale engineering or construction works. For this purpose, and in order to review the long-term possibilities for home production of silica sand, we determined resource potential nationally.

Our approach was (1) to establish the relevant conditions and processes associated with the deposition of the currently exploited sands, (2) identify lithostratigraphic units that are genetically similar or are otherwise known to contain quartz-rich sands, and (3) query the Dutch geological survey's borehole database for potential silica sand occurrences within those units. As we have to rely on non-dedicated data, the latter step was undertaken using a largely qualitative set of lithological search parameters. Finally, a limited number of available chemical analyses was used for preliminary verification purposes.

Using this approach, we identified three prospective areas: one in the north of the province of Limburg and east of the province of Noord-Brabant (~750 km^2), one in the central south of Noord-Brabant (~45 km^2), and one in the east of the Gelderland and Overijssel provinces (~1,200 km^2). For each area, first-order characteristics of possible silica sand resources are presented (type of deposit, depth, approximate thickness). In the terms of current reporting conventions, we resolved silica sand occurrence to the level of 'reconnaissance mineral resource' or 'exploration result', and our results do not constitute a formal resource declaration. Available chemical data suggest that the resources in the first two areas could be or become economic, although the grades are lower than those of the currently exploited resources. The third area is less promising in that respect, but available data is too limited to reject the area in this stage. Even so, we tentatively conclude that home production of silica sand can probably be maintained after the reserves in Limburg are depleted.

Keywords: Netherlands, industrial minerals, silica sand, resource potential.

Introduction

Silica sand, '*zilverzand*' (silver sand) in Dutch language and also referred to as industrial sand or quartz sand, is natural or processed sand that consists (almost) entirely of quartz grains (SiO_2). Rather than as aggregate, e.g. for concrete, it is used as a quartz resource for several applications. Dutch consumption amounts to about 1.5 Mt/a (Fig. 1), about 55% of which is used by the glass industry, 20% by the ceramic industry, 15% by the chemical industry and 10% in foundries (Van der Meulen et al., 2007a). The Netherlands is about 50% self-sufficient. Two companies in Limburg, the southeasternmost province of the country, extract high-grade Miocene silica sand in the vicinity of the town of Heerlen, from resources that rank among the purest in Northwestern Europe (Figs 2, 3). A few smaller operators extract lower-grade silica sand in the same area, for lower-grade applications.

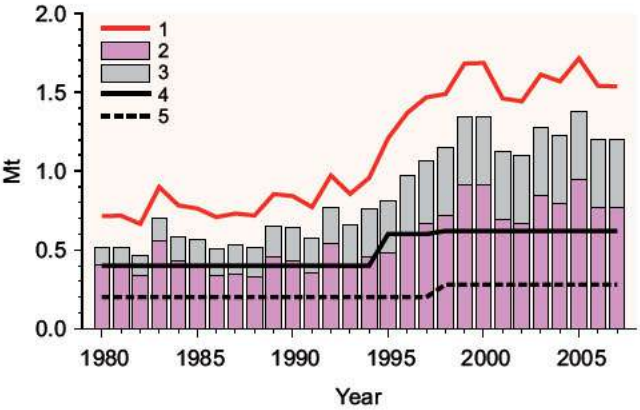


Fig. 1. The demand for silica sand in the Netherlands from 1980 to 2007 (1), and its provision by home production (2), secondary materials (3) and imports (4). Secondary substitution of silica sand is largely achieved by glass-packaging recycling (~80%; cf. Anonymous, 2002). High-grade silica sands are exported to Germany, Belgium and France (5). Sources: National Commission for the Co-ordination of Mineral Planning Policy (LCCO, The Hague) and data at the disposal of the authors. (2) through (5) are estimated figures.

Compared to Dutch resources of, e.g., filling sand and clay, silica sand is scarce and therefore subject to the so-called building materials assessment (*'bouwgrondstoffentoets'*; Anonymous, 2004a; Van der Meulen, 2005a-b). The assessment aims to raise the awareness of mineral resources and interests when planning for large-scale engineering or construction works (hydraulic engineering, infrastructure, urban development, land reconstruction, etc.). Project areas have to be assessed for scarce minerals, in order to avoid their (unintended) sterilisation, and to stimulate their exploitation in conjunction with the work at hand. The clearest example of this approach is the combination of river widening and gravel extraction along the river Meuse (Silva & Kok, 1996, Van der Meulen et al., 2006). Note that silica sand is explicitly covered by the building materials assessment, even though it is not a building material but an industrial mineral.

Conducting the building materials assessment requires the use of geological information. For this purpose, the Geological Survey of the Netherlands developed *'Delfstoffen Online'* (Minerals Online): a nation-wide, web-based information system that provides first-order, regional-scale information on Dutch superficial / shallow mineral occurrences (TNO, 2009a). In a series of papers written in support of this tool, on aggregates in Van der Meulen et al. (2005) and on clay in Van der Meulen et al. (2007b), the present contribution reviews published and unpublished silica-sand resource information.

Available data and resource inventory methodology

Previous work, general approach

The ground work for the present inventory was lain by the Geological Survey in the late 1990s and early 2000s. In 1996-1998, the southern-Limburg occurrences were assessed for mineral-planning purposes (Westerhoff, 1996; Dubelaar & Menkovic, 1998), and in 2002 a reconnaissance study was conducted in the remaining parts of the country, in order to review the long-term possibilities for home production of silica sand (Gruijters & Menkovic, 2002). The latter assessment was to include sands having qualities below the current cut-off grades of Dutch producers, but which would qualify for upgrading in

Fig. 2. Satellite image of Heerlen (©Google 2009), where two operators extract high-grade silica sand (for location see Fig. 3).

Fig. 3. Reference map, showing the geology of the Netherlands and the outlines / locations of other maps and photos.

other countries. For that matter, note that the British Geological Survey defines silica sand as having *'a high proportion of silica (up to 99% SiO_2) in the form of quartz'* (BGS, 2006). The top of the range in the United Kingdom appears to equate to the minimum standard for moderately-grade silica sand in the Netherlands, as defined below.

We used the data of all three assessments to arrive at resource information that meets the requirements of the aforementioned online minerals information system. If available and when necessary, we incorporated more recent data and insights. Our general approach was to:

1. identify relevant properties of the known silica-sand resources in southern Limburg (lithological, genetic);
2. establish whether (some of) these properties occur elsewhere in the country;
3. map them, where possible; and
4. verify the results preliminarily with chemical data, if available.

As Van Loon (this issue) discusses the early diagenesis of the southern-Limburg silica sands in considerable detail, we limit our own description of this process to a minimum, and discuss other factors that bear to their formation as a mineral resource. Our primary data sources were (1) DINO, a digital archive of subsurface data developed and maintained by the Geological Survey of the Netherlands, and (2) DGM, a geological model of the Dutch shallow subsurface that was also developed by the Geological Survey.

DINO

DINO (TNO, 2009b) currently contains more than 400,000 standardised borehole descriptions, i.e. ~10 per km^2 on average, and it is the single largest dataset of its kind in the country. It contains the Geological Survey's boreholes, mostly drilled for geological mapping purposes, and a variety of third-party data. However, only a negligible number of boreholes has chemical analyses that are required to establish silica-sand quality. We therefore queried the data for potential rather than proven silica sands, using a predominantly qualitative set of search parameters, i.e. a combination of lithostratigraphic and lithological criteria. The exact criteria vary per area, and are detailed below.

DGM

DGM (Digital Geological Model) is a national 2.5D, 'stacked grid-layer model' of the boundary surfaces of all Neogene and Quaternary formations in the Dutch onshore domain (De Mulder et al., 2003; TNO, 2009c). The model was constructed by interpolating ~16,500 lithostratigraphically interpreted boreholes, a subset from DINO that was created to arrive at an even distribution of good-quality borehole data over the country. The resolution, i.e. the size of the grid cells, is 100 × 100 meters.

Lithostratigraphic boundary surfaces were interpolated between the corresponding transitions in each borehole. In principle, these transitions were identified in lithologic logs, but where necessary geophysical well-log data was used as well. Additional, non-borehole information was used to guide the interpolation process deterministically, in situations where mere statistics can not be expected to produce a geologically sound result. This information includes the (inferred) distribution of each unit, faults, and sedimentary features such as basins and large-scale channels. Generally, guiding took place by adding 'virtual' points to the interpolation set.

The basal surface of each unit was interpolated using a block-kriging algorithm (Isaaks & Srivastava, 1989; Goovaerts, 1997). The top surfaces, obtained indirectly, are the combined basal surfaces of overlying units.

Assessing silica sand quality

Table 1 shows the quality requirements for silica sand in its main applications, given as maximum shares of non-silicon constituents. Purity is expressed chemically, i.e. as shares of oxides rather than of minerals, as testing is commonly carried out by chemical analysis (XRF, ICP). Iron (Fe_2O_3) would typically be related to limonite and goethite grain coatings, and possibly to glauconite. A share of aluminium (Al_2O_3) is mainly caused by clay minerals (including glauconite; feldspar is less likely in currently exploited Dutch silica sand resources). Titanium (TiO_2) is indicative of rutile or ilmenite. Depending on the application, additional parameters may include grain size distribution, and the contents of chromium (Cr_2O_3) and heavy minerals. The tabled figures are end-product specifications, which are usually not met by raw, i.e., unprocessed silica sand (Table 2). Clay is removed by washing or wet screening. Grain coatings of iron minerals may be removed by attrition (scrubbing), or acid leaching (cold or hot). Froth flotation and magnetic or gravity (spiral) separation are used to remove discrete contaminant minerals. The silica sands that are currently exploited in the Netherlands usually only require washing, or the combination of washing and attrition.

Resource potential indicators inferred from the Limburg deposits

Stratigraphic occurrence and genetic factors

The silica sands of southern Limburg occur predominantly in the Heksenberg Member and locally in the Vrijherenberg Member, the two uppermost subunits of the Miocene marine Breda Formation (Figs 4, 5; all formations cf. De Mulder et al., 2003). In its outcrop area, the Heksenberg Mbr consists of well-sorted, fine-grained sands that were deposited on the beaches and tidal flats rimming the southern North Sea Basin during the Middle Miocene. The unit has two lignite intercalations, the Morken and Frimmersdorf seams (belonging to the Ville Fm.), both resulting from the progradation of coastal and lacustrine peat swamps from the east (Schäfer et al., 2005; Wong et al., 2007; Figs 5, 6). The seams correlate to the well-known thick lignite deposits that are exploited for fuel 20 - 40 km to the east in Germany, in the Garzweiler, Frimmersdorf and Hambach quarries, operated by Rheinbraun Brennstoff GmbH.

The source material for the Heksenberg Mbr probably originated from the well-weathered and therefore quartz-rich material that was available at the margins of the southern North Sea Basin in Belgium and adjacent areas. The uniform grain-size distribution of the silica sand deposits is consistent with longshore transport and coastal sorting processes. Early diagenetic leaching by humic acids originating from the peat increased silica sand purity by dissolving non-quartz components, i.e. in a process comparable to podzolisation (Kuyl, 1973; Van Loon, this issue). Other than being a normal process associated with organic deposits, leaching can be inferred from the fact that the purest silica sands are indeed associated with the lignite seams. In addition to that, Mörs (2002) argues that

Table 1. Matrix of five categories of silica sand (1 - 5), and their applications in the structural ceramic industry (A), foundries (B), low-grade glass (C), fine ceramics (D), high-grade glass (E), water glass and zeolites (F), and carborundum (SiC) (G). The quality per category is given in terms of minimum quartz (SiO_2) and maximum iron (Fe_2O_3), aluminium (Al_2O_3) and titanium (TiO_2) contents, and the maximum loss on ignition (LOI). These are figures for processed silica sand, quality indications for raw sands are given in table 2. Modified from Feenstra & Mulder (2003); reprinted from Van der Meulen et al. (2007a).

Categories	Applications							Chemical characterization					
	A	B	C	D	E	F	G	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	LOI	Heavy minerals
1					■	■	■	99.80	0.01	0.05	0.02	0.05	no fusible heavy minerals
2				■	■	■	■	99.70	0.02	0.08	0.03	0.10	no criterion
3				■	■	■		99.50	0.03	0.14	0.04	0.25	no criterion
4		■	■					99.0	0.1	0.2	0.1	0.5	no criterion
5	■	■						97.0	0.5	0.5 - 1.0	0.3	1.0	no criterion

Table 2. *Quality indication for wet-screened raw silica sands, based on common practice among Dutch silica-sand producers (Feenstra & Mulder, 2003).*

Element	Quality indication			
	Excellent	High	Moderate	Low
SiO_2	99.75	99.5	99.0	97.0
Fe_2O_3	0.01	0.03	0.06 - 0.1	0.5
Al_2O_3	0.1	0.2	0.4	1.0
TiO_2	0.02	0.04	0.1	0.3
LOI	0.1	0.2	0.5	1

the general lack of fossil material in the lignite, formed in a sedimentary environment that was undoubtedly biologically productive, points to dissolution. The intensity of leaching and soil-forming processes has probably been climatologically enhanced: as evidenced by biostratographical dating of the Frimmersdorf seam at the Hambach quarry, the Heksenberg Mbr was deposited during the Mid-Miocene climatic optimum, just before the Late Miocene/Pliocene cooling phase (Utescher et al., 2000; Mörs, 2002; Wong et al., 2007).

The Heksenberg Mbr is transgressively overlain by the marine and coastal deposits of the Vrijherenberg Mbr, which consists predominantly of argillaceous and glauconite-bearing sands (marine facies), but locally contains silica sand as well (coastal facies). The conditions were largely comparable to those during Heksenberg deposition, but the favourable coastal sorting and leaching processes shifted to the east, outside of the area of interest (Fig. 4), and deepening came with an autigenic deleterious admixture.

The association of silica sand with peat was not only important because of leaching. In later stages, the lignite seams probably acted as adsorption filters, which reduced the mineral content of percolating groundwater. Apart from that, their impermeability reduced water percolation altogether. In view of the post-depositional geology and geohydrology of the area, this 'conservation capability' of lignite was an important secondary factor that contributed to silica sand quality.

Post-depositional conditions

Situated at the northern edge of the Ardennes, southern Limburg became uplifted from the Mio-Pliocene transition onwards (Van den Berg & Van Hoof, 2001; Van Balen et al., 2005; Westerhoff et al., 2008). At that time, the area had become a tidal to fluvial sedimentary environment, where an alternation of sand, gravel, clay and lignite was deposited: the Upper Miocene to Pliocene Kieseloolite Fm., which unconformably overlies the Breda Fm. (Fig. 4). Denudation of the well-weathered hinterland, the Rhenish Massif, initially still yielded mature, quartz-rich sediments (Westerhoff, 2009). In fact, the Kieseloolite Fm. contains sands that would qualify as (lower-grade) silica sand, but they are not exploited at present.

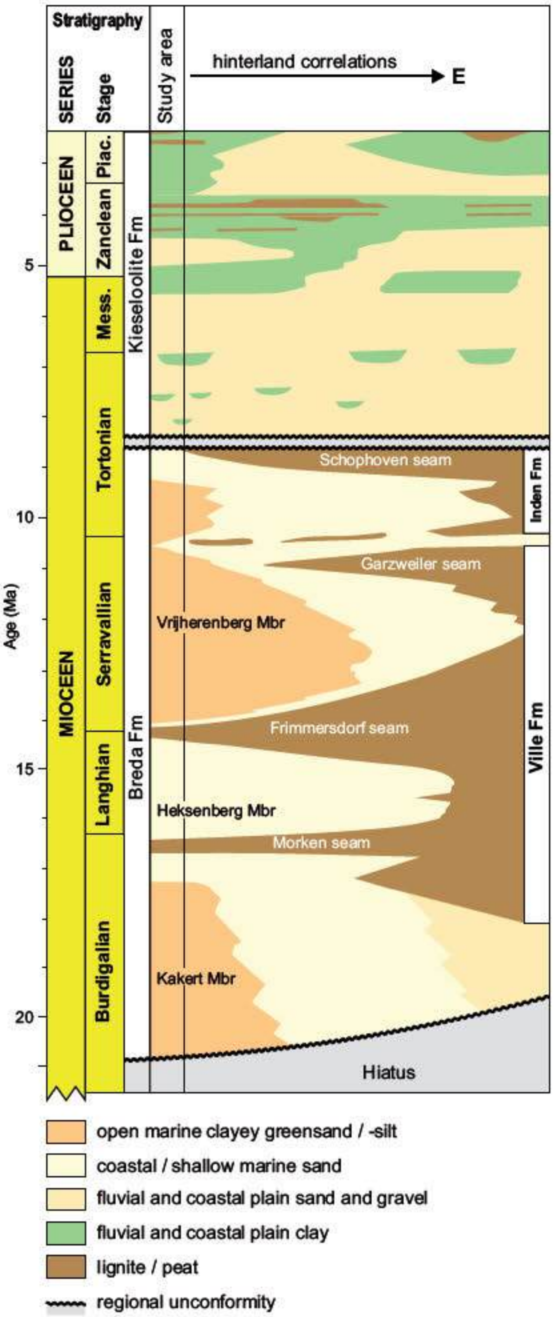
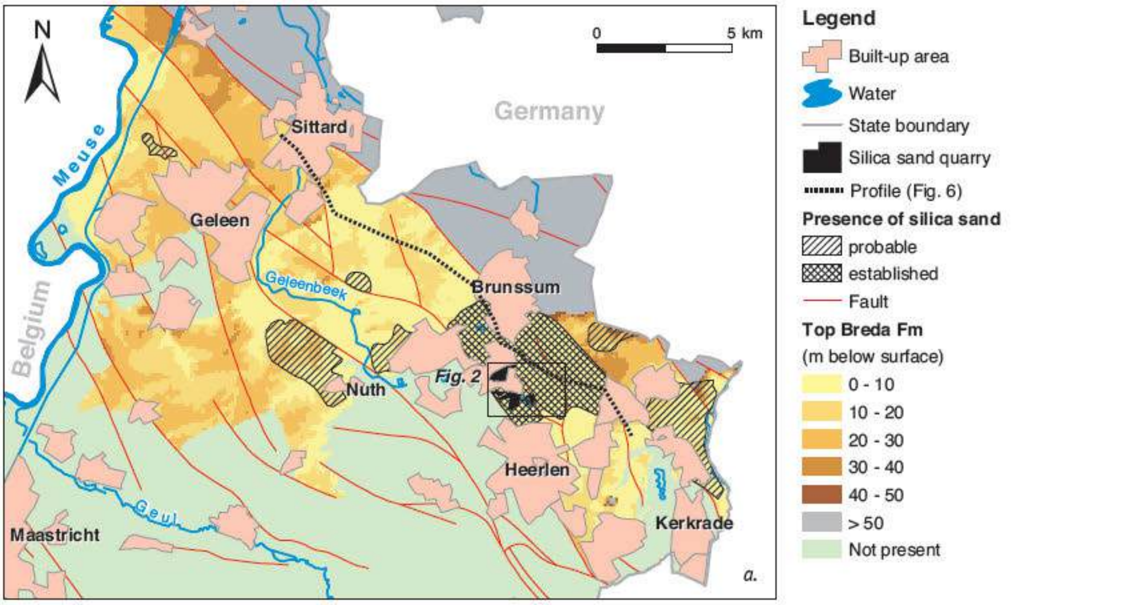
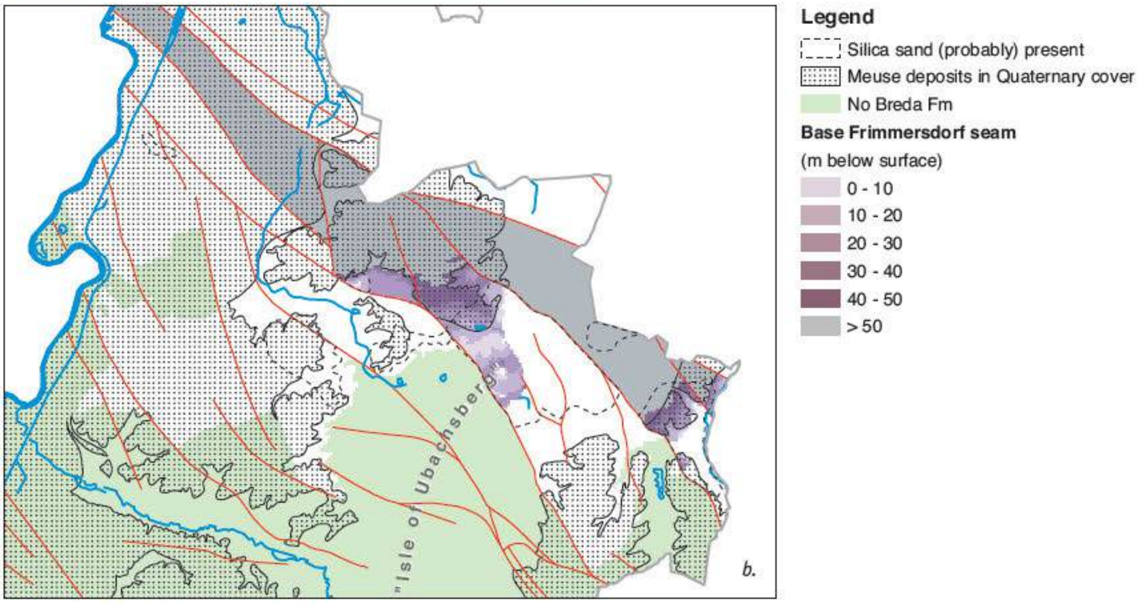


Fig. 4. The Burdigalian to Piacenzian of Southern Limburg and adjacent part of Germany, showing stratigraphic relationships and main lithologies of relevant units discussed in the text. The eastward extension with respect to the study area, which corresponds to some tens of kilometres, is included for better illustration of the overall stratigraphic development ('hinterland correlations'). Modified from Wong et al. (2007).

By the Late Pliocene, deposition of the Kieseloolite Fm. ceased, the area turned into erosional, and the Meuse river system came into existence. Due to tectonic processes, the catchment of the Meuse was larger than that of its predecessor systems, and progressive uplift lead to stronger and deeper erosion. Accordingly, Meuse sediments are coarser and more polymict than those of prior units (Westerhoff, 2009). Up until the Early Pleistocene, a first, eastern course of the Meuse





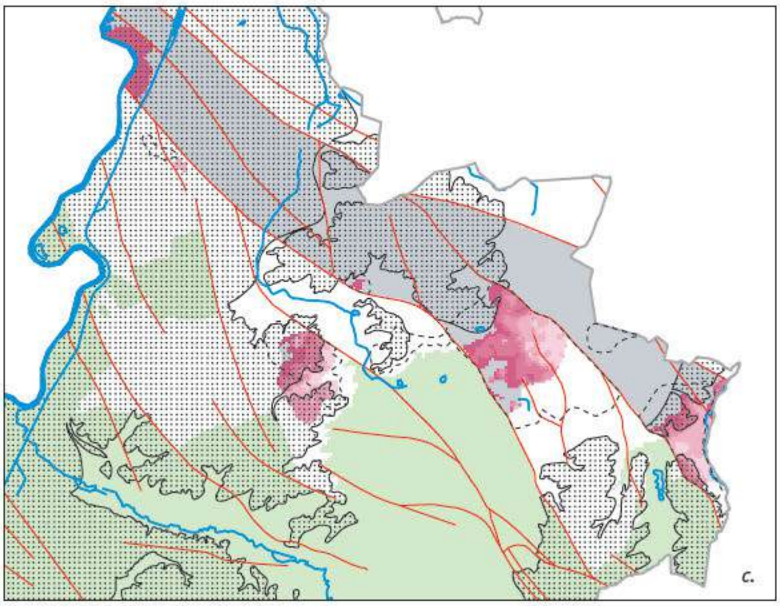


Fig. 5. a. the occurrence of silica sand in southern Limburg (see Fig. 3 for location). The top of the Breda Fm. is shown because most silica sand in the area occurs below this level. b and c show the base of the Frimmersdorf and the top of the Morken lignite seam, respectively: these layers delimit the highest-quality silica sand occurrences of the Heksenberg Mbr (see text). The occurrence of Meuse deposits is shown because of the potential impact of deposition on silica-sand quality. The top-Breda Fm. grid is extracted from DGM (TNO, 2009b, see text), the lignite-seam grids from Regis, a national hydrogeological model of all major aquifers and aquitards (Vernes et al., 2005, 2009). The lignite layers may be discontinuous within their distribution areas.

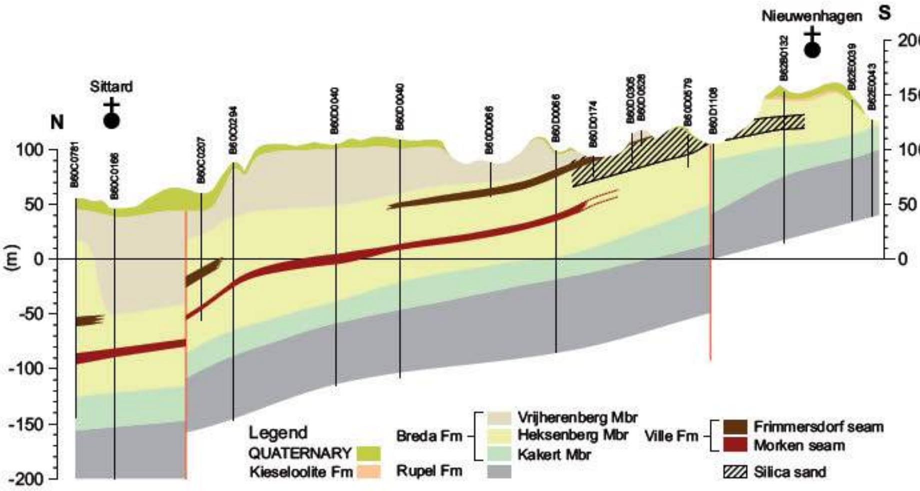


Fig. 6. Profile through southern Limburg (see Fig. 5a for profile line), showing the occurrence of silica sand.

occupied the so-called East-Meuse valley, as a tributary of the Rhine (Juvigné & Renard, 1992; Kuyl, 1980; Westerhoff et al., 2008). Due to tectonic movements around the Early to Middle Pleistocene transition, the Meuse shifted towards the west and formed the valley it still occupies along the Dutch-Belgian border.

Under conditions of ongoing uplift, which accelerated in early Mid Pleistocene times, the sediments of the incising Meuse (Beegden Fm.) have been preserved in terraces that cover the flanks of both river valleys (Van Balen et al., 2005; Westerhoff et al., 2008). To a varying extent, iron-bearing water originating from the highly permeable Meuse sediments, and possibly also from the oxidation of the glauconite in the Vrijherenberg sands, infiltrated the Heksenberg sands, which reduced their quality as a quartz resource. This applies especially at places where the Meuse eroded the lignite seams. The former East-Meuse and present Meuse valleys are separated by an approximately SW-NE trending zone around Heerlen, the so-called 'Isle of Ubachsberg'. The best currently exploited silica sands, never affected directly by the Meuse, are located in this zone (Fig. 5b).

Resource potential elsewhere in the Netherlands

Candidate units

In summary, silica sand resources in Limburg are a product of (1) a quartz-rich source area, (2) a specific coastal environment and (3) favourable post-depositional conditions. The highest-quality silica sands are generally found where lignite is present and an iron-bearing / yielding overburden is absent, but high-grade silica sand deposits also occur where the latter two conditions are not met. This set of generic conditions explains the occurrence of the Limburg silica sands in first order only: resource quality is known to vary from the highest to lesser grades even within individual quarries. As all of the aforementioned processes and conditions have a certain degree of spatial and/or temporal variation, this is to be expected. However, in spite of its importance to silica sand exploration, such heterogeneity cannot be resolved when prospecting on national scale with non-dedicated data. Altogether, this precludes the present study to be more ambitious than an identification of areas of enhanced resource potential.

The exact above combination of (dia)genetic factors is limited to southern Limburg altogether. For the remaining parts of the Netherlands, we searched for potential silica sand deposits on the basis of a lesser number of factors, i.e. in lithostratigraphic units that share general lithological characteristics with the Heksenberg Mbr, have been deposited in comparable depositional environments, or are otherwise known to contain quartz-rich sands. These criteria are met by the aforementioned Kieseloolite Fm., the Lievelde Mbr of the Upper Miocene to Pliocene shallow marine Oosterhout Fm., the Upper Pliocene to Lower Pleistocene fluviatile Peize Fm., and Pleistocene Stramproy Fm. of mixed continental facies (Table 3).

Querying for silica sand

Within the candidate units, potential silica sand was searched with median grain sizes between 80 and 320 μm (in case of measured grain size data), or belonging to sand median classes very fine to moderately coarse (≥105 and <300 μm; classification cf. Anonymous, 1989, 1990). The queried range more or less coincides with the grain sizes preferred by the industry. We used a somewhat higher upper limit, in order to enhance mapping consistency. High quartz contents are assumed when sands are light-coloured, having colour attributes white, greyish-white, yellow-white, etc. This is a relatively safe assumption for Dutch sands, in which non-quartz components are usually darker-coloured. Light-coloured non-quartz sands (e.g. feldspar and calcareous arenites) do not occur.

The data query was limited to 50 m below the surface. As a result of a downward decreasing borehole data coverage, we do not expect to be able to map such narrowly-defined, 'exotic' lithologies successfully below this depth. The range comprises current silica sand exploitation depths.

Table 3. Main characteristics of lithostratigraphic units with an assumed potential for silica sand occurrence.

Formation	Member (stratigraphic delimitation)	Location (topographic delimitation)	Depositional environment	Main characteristics (of member / at location)
Stramproy Fm.	not applicable	Southern Noord-Brabant	fluvial, aeolian, periglacial	fine to medium-grained, quartz-rich sands
Kieseloolite Fm.	not applicable	Eastern Noord-Brabant, southern Limburg	fluvial, tidal	medium to coarse, quartz-rich sand, locally gravel bearing, intercalations of (peaty) clay may occur
Oosterhout Fm.	Lievelde Mbr	Eastern Gelderland and Overijssel	coastal	well sorted, fine, quartz-rich sands, silicified horizons
Breda Fm.	Vrijherenberg Mbr	Southern Limburg	coastal, shallow marine	well sorted fine to medium quartz sands, pre-dominantly glauconite-bearing and argillaceous
	Heksenberg Mbr	Southern Limburg	coastal	Well sorted fine to medium quartz sands

Query results

The data query yielded occurrences in 534 boreholes, that appeared to be clustered in three prospective areas (A-C). A fourth area in central Limburg (indicated as 'not mapped' in Fig. 3) showed some scattered occurrence of white sands, but the quality of the available data precluded successful elaboration.

Prospective area A is located in eastern Noord-Brabant and northern Limburg, and consists of two northwest-southeast trending subzones, separated by a horst-like structure (Fig. 7). The eastern subzone ranges from the town of Cuijk to Venlo, the western one is located just north of the town of Deurne. Sands with the desired characteristics occur in the Kieseloolite Fm., alternating with lignite, clay, or sands that do not meet the search criteria. The formation overlies the Breda Fm., here of a deeper marine facies than in southern Limburg, and it is either overlain by Quaternary Rhine / Meuse deposits (of the Kreftenheye, Waalre and Beegden Fms), or by the predominantly aeolian periglacial deposits of the Boxtel Fm.

Inspection of boreholes in the area reveals that potential silica sand occurs throughout the Kieseloolite Fm., except for in the deepest and thickest part in the west. Presence/absence appears to be associated with facies such as channels, which cannot be captured at the given borehole density. We therefore characterise potential silica sand occurrence in area A with maps of the top and base of the Kieseloolite Fm., with the annotation that not all the sediments contained between these surfaces meet our search criteria.

The depth of the top of the Kieseloolite Fm. varies between 0 and 40 m, averaging at about 16 m; the base varies between 10 and 100 m, averaging at about 30 m. The cumulative thickness of potential silica sands (Fig. 8) ranges between 2 and 20 m, with an average (modal) thickness of about 8 m, this amounts to about 45% of the thickness of the Kieseloolite Fm. Thickness statistics were obtained by interpolating the highest and lowest occurrences of white sands within the Fm. We do not display the interpolation results spatially, because of the aforementioned undersampling.

Chemical analysis on 7 wet-screened samples (Feenstra & Mulder, 2003, Table 4) resulted in quartz percentages ranging from 96.8 to 99.5, meeting the criteria for low to high-grade raw silica sands (Table 2). Earlier analyses on unscreened samples show percentages 97.65 to 98.65 (Gruijters & Menkovic, 2002).

Prospective area B is located in the province of Noord-Brabant, near the village of Goirle (Fig. 9). White sands with the queried characteristics occur in the Stramproy Fm., which either crops out or is overlain by a thin cover of the aforementioned Boxtel Fm. The Stramproy Fm. consists predominantly of aeolian sands and the deposits of rivers that drained a composite catchment area stretching from central and northern Belgium towards the northeast. The unit is of Early to Middle Pleistocene age, and deposition took place partly under periglacial conditions. The formation overlies the fluvial deposits of the Waalre Fm., but note that these units may elsewhere have other, more complex relative stratigraphic positions than the superposition observed here.

Within the formation, white sands alternate with silts and clay. We characterised potential silica sand occurrence with the upper and lower formation boundary surfaces, again with the annotation that not all the sediments contained between these surfaces meet our search criteria. Cumulative thickness of potential silica sand averages at about 4 m, which equates to about 40 - 45% of the thickness of the Stramproy Fm. in the area.

Chemical analysis on 2 wet-screened samples (Feenstra & Mulder, 2003, Table 4) resulted in quartz percentages of 99.0 and 99.1, meeting the criteria for moderately-grade raw silica sands (Table 2). Earlier analyses on unscreened samples show peak percentages of 98.10 to 99.14% (Gruijters & Menkovic, 2002).

Prospective area C is located in the eastern Gelderland and Overijssel provinces and stretches approximately from the town of Almelo to Doetinchem, in a north-south orientation (Fig. 10). White sands with the desired characteristics occur in the upper part of the Oosterhout Fm. as well as scattered in the

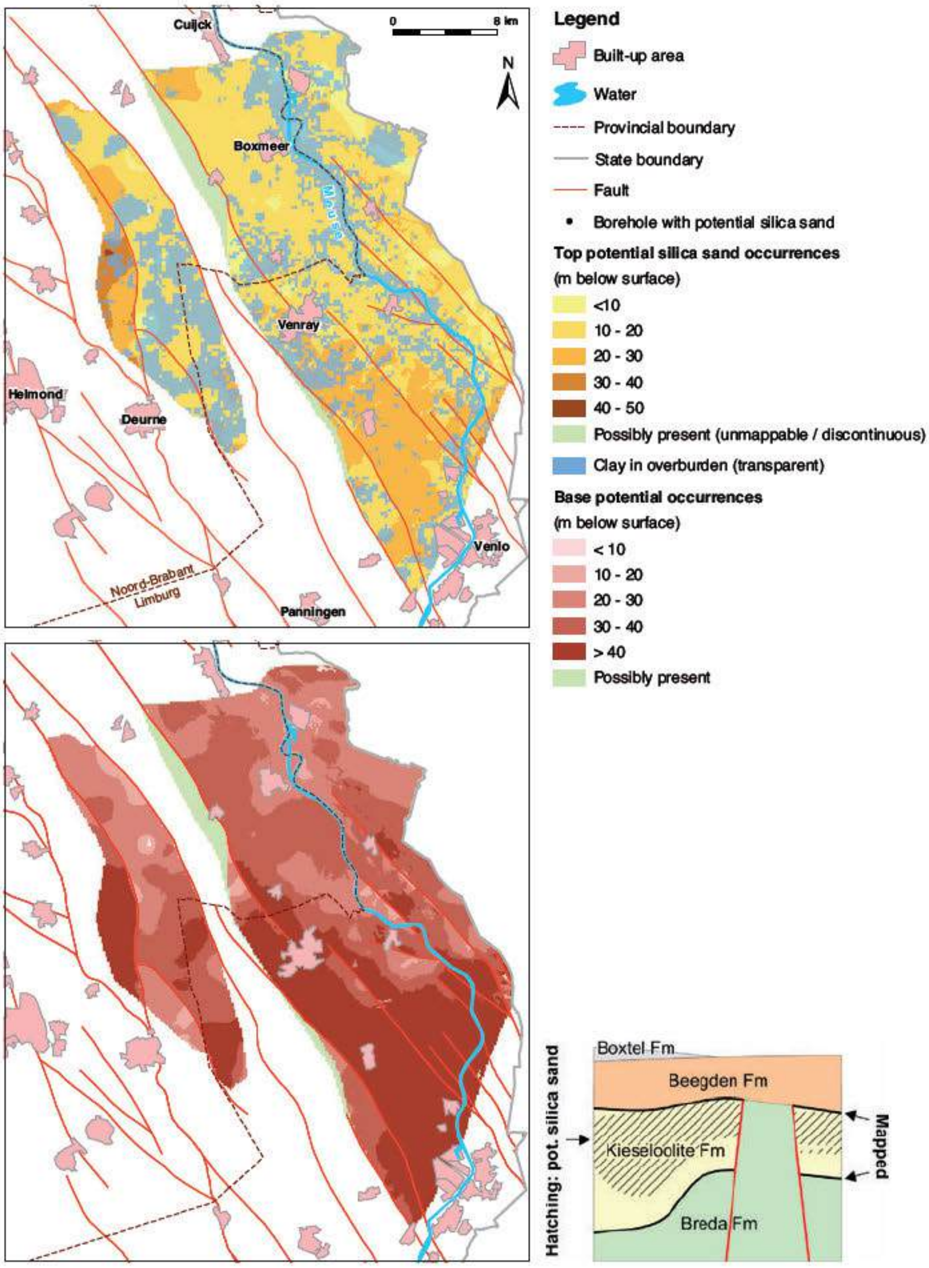


Fig. 7. Prospective area A (see Fig. 3 for location). Resource position is indicated with the top and base of the Kieseloolite Fm. Potential silica sand occurs between these surfaces but, as shown schematically by the inlay, not exclusively (see text for further explanation). 'Clayey overburden' is based on clay resource data presented by Van der Meulen et al. (2007b). The cumulative resources thickness is given in Fig. 8. Borehole data in Gruijters & Menkovic (2002).

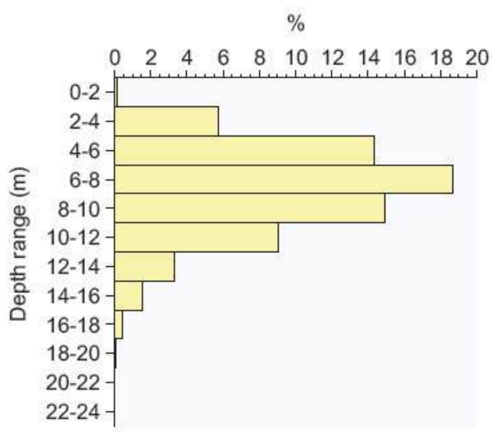


Fig. 8. Histogram of the thickness of potential silica sand deposits in prospective area A (see text for explanation).

overlying Peize Fm. The sedimentary succession of interest is comparable to the Upper Breda – Kieselooliet Fm. succession in southern Limburg, and consists of shallow marine, clayey and glauconite-bearing sands grading, via clayey sands, into well-sorted, quartz-rich, sandy tidal deposits. The latter sediments are stratigraphically distinguished as the Lievelde Mbr (note that the homonymous unit defined by Van den Berg & Gaemers (1993) included the clayey and glauconite-bearing deposits as well). The Peize Fm. was deposited by east-west flowing rivers of the fossil Eridanos system, which drained the area of the present Baltic sea and surroundings, and built a huge delta into the North Sea Basin (Overeem et al., 2002; De Mulder et al., 2003). Its catchment was generally well-weathered and yielded quartz-rich sands; in that respect the provenance situation of the Lievelde sands was comparable to that of southern Limburg

Table 4. Chemical analyses for silica sand samples in prospective area A-C (data from Gruijters & Menkovic, 2002).

Area	Borehole	Screened	Method	SiO_2	Fe_2O_3	Al_2O_3	TiO_2
A	46B0156	yes	ICPAES	99.0	0.06	0.50	0.08
A	46B0156	yes	ICPAES	99.5	0.03	0.22	0.02
A	46G0073	yes	ICPAES	96.8	0.11	1.64	0.10
A	46B0125	yes	ICPAES	98.4	0.08	0.73	0.07
A	46D0139	yes	ICPAES	98.8	0.05	0.60	0.02
A	46D0139	yes	ICPAES	97.5	0.37	1.03	0.19
A	52E0171	yes	ICPAES	98.6	0.12	0.61	0.03
A	46C0124	no	XRF	98.5	0.06	0.83	0.00
A	46C0124	no	XRF	98.3	0.12	0.78	0.03
A	46C0124	no	XRF	98.7	0.05	0.55	0.00
A	46C0124	no	XRF	98.4	0.07	0.72	0.00
B	50G0367	yes	ICPAES	99.0	0.08	0.46	0.06
B	50G0090	yes	ICPAES	99.1	0.06	0.39	0.05
C	28D0213	yes	ICPAES	96.6	0.22	1.66	0.10

during deposition of the Heksenberg sands. With respect to the Breda and Kieseloolite Fms, however, the sediments of the Peize Fm. contain higher percentages of instable heavy minerals, with dominance of garnet. The Oosterhout – Peize suite is unconformably overlain by the fluviatile sands of the Urk Fm., ice-pushed deposits (belonging to various formations) and related (peri)glacial sediments of the Drente Fm., the Kreftenheye Fm., and/or the periglacial deposits of the Boxtel Fm.

The only regionally mappable feature associated with potential silica sand occurrence in area C is the boundary surface between the Oosterhout and Peize Fms. Most potential silica sand occurs immediately or just below this level, only the scattered Peize occurrences lie above. A lower resource delimitation cannot be provided: instead of with some mappable feature, it appears to be associated with facies units, the variation and distribution of which cannot be captured at the given borehole density. We characterise silica resource occurrence in area C with a map of the top of the Oosterhout Fm. only, plus an indication of the cumulative thickness of the underlying potential silica sand deposits. The depth varies between 0 and 50 m (our search limit), averaging at about 16 m. The cumulative thickness of potential silica sand (Fig. 11) ranges between 2 and 22 m, with an average (modal) thickness of about 7 m. Thickness statistics were obtained in the same way as for area A.

Only one wet-screened sample in area C has been analysed for silica sand quality, testing below the demands (Table 2) for low-grade raw silica sand (SiO_2 96.6%, table 4). The extent to which this material can be upgraded (scrubbing, leaching, etc., see above) has not been determined, and we do not wish to reject area C as prospective on the basis of a single observation. However, also on the basis of provenance and qualitative lithological descriptions, industrial-grade silica sand occurrence is less likely than in areas A and B. The only active sand pit in area C, the Markelo site operated by Dyckerhoff Basal BV, reaches appropriate depths and the product is clearly white (Fig. 12), but it is used as concrete aggregate, not as a quartz resource.

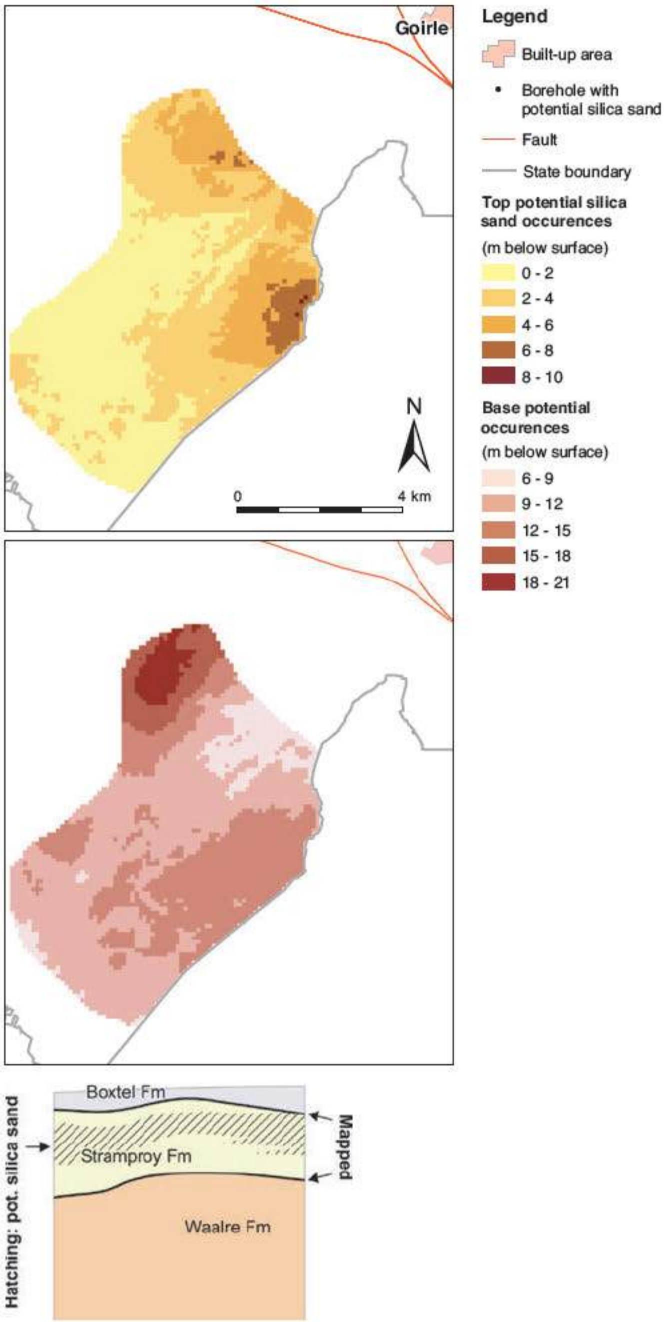


Fig. 9. Prospective area B (see Fig. 3 for location). Resource position is indicated with the top and base of the Stramproy Fm. Potential silica sand occur between these surfaces but, as shown schematically by the inlay, not exclusively (see text for further explanation). 'Clayey overburden' is based on Van der Meulen et al. (2007b). Borehole data in Gruijters & Menkovic (2002).

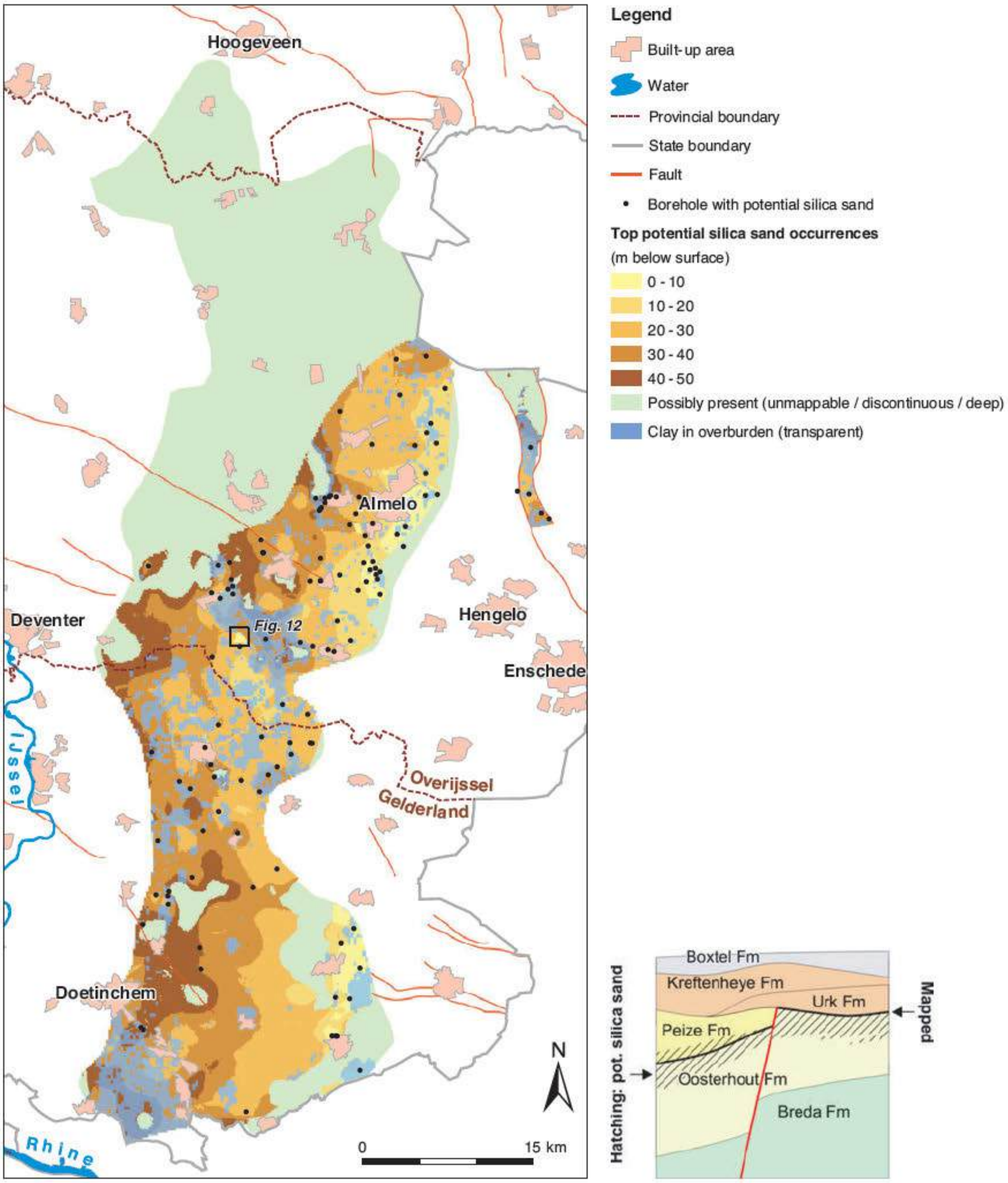


Fig. 10. Prospective area C (see Fig. 3 for location). Resource position is indicated with the top of the Oosterhout Fm.; the inlay shows the schematic relationship between this surface and potential silica sand occurrence (see text for further explanation). 'Clayey overburden' is based on Van der Meulen et al. (2007b). The cumulative resources thickness is given in Fig. 11. Borehole data in Gruijters & Menkovic (2002).

Discussion and conclusions

We identified three prospective areas for silica sand, in a two-step query of lithostratigraphic and borehole data, searching for combinations of favourable depositional processes and appropriate lithological characteristics. The spatial consistency of the query results suggests that our approach is basically sound. The qualitative lithological search parameters that we used are fairly generic, and would most probably not have been diagnostic enough for silica sand occurrence without narrowing the query down with stratigraphic and provenance criteria. Our inference that areas A and B are the most prospective two is also spatially consistent in the sense that they are aligned with known silica sand deposits in southern Limburg, northern Belgium and North Rhine-Westphalia (see also Van Loon, this issue). Altogether, conditions at the southern margin of the Mio-Pliocene North Sea Basin appear to have been favourable for silica sand deposition.

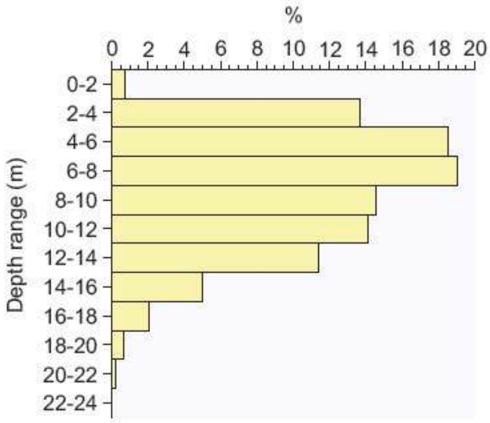


Fig. 11. Histogram of the thickness of potential silica sand deposits in prospective area C (see text for explanation).

We set out to provide silica sand resource information that meets the requirements of the aforementioned building materials assessment. We consider resource potential to be sufficiently resolved for such purpose, especially for the first step, which is to establish whether mineral occurrence can be excluded, or needs to be further explored in conjunction with some spatial planning issue, engineering work, etc. Other than that, our study can be considered a pre-prospecting effort for commercial silica sand exploration. In the terms of the code for reporting of mineral exploration results, mineral resources and mineral reserves (Anonymous, 2001; see also Anonymous, 2004b), the potential silica sand occurrences would classify as 'reconnaissance mineral resources'. These are '*based on regional geological studies and mapping, airborne and indirect methods,*

Fig. 12. The Markelo sand pit located in prospective area C (see Fig. 10 for location). The product is almost as white as the Heksenberg sands (Fig. 2), but it is used as aggregate, not as silica sand. Satellite imagery ©Google 2009.

preliminary field inspection, as well as geological inference and extrapolation. The aim is to identify areas of enhanced mineral potential worthy of further investigation towards deposit identification. The level of confidence is lower than that applying to an inferred Mineral Resource and is usually not sufficient to quote tonnage and grade figures'. 'Reconnaissance mineral resources', reports of which are to be used only for mineral or spatial planning purposes by the government, is no terminology in the more recent PERC reporting code (Anonymous, 2008), because this specifically applies to public reporting by the extractive industry. In the terms of this code, our results classify as 'exploration results', and do not constitute a formal resource declaration.

Note that if southern Limburg would be assessed in the same way as the rest of the country, the resulting prospective area would be substantially larger than the extent of the known silica sand resources. This illustrates the difference between determining resource potential and a dedicated resource assessment. Establishing silica sand quality is a specialist undertaking that involves a drilling campaign and chemical analyses. Beyond that, it involves subjecting drilling samples to common silica-sand processing steps, the results of which determine whether or not the deposit is economic.

Notwithstanding the need for further study, available chemical analyses do suggest that there are deposits, at least in area A and B, that could be or become economic, provided that quantities and depths allow for exploitation. Combined with geological considerations, the analyses also suggest that the silica sand qualities and quantities that occur in southern Limburg are not to be expected elsewhere in the Netherlands. Nonetheless, given the low level of consumption (in comparison with regular aggregates), we preliminarily conclude that there are possibilities to maintain home production of silica sand beyond the duration of the operations in southern Limburg, at least to some degree.

The aggregate volume of sand that we identified as potential silica sand, obtained by multiplying the surface areas and modal resource thicknesses for areas A-C, amounts to 6 or 15 km^3 roughly, depending on whether area C is included. We provide this figure, which is a huge overestimation of the actual resources with no practical use, in order to underline the scarceness of silica sand in the Netherlands. Dutch gravel resources are estimated at about 12 km^3, and about half of that amount is considered technically exploitable (Van der Meulen et al., 2005). At extraction rates in the same order as those of silica sand, Dutch gravel is generally considered a scarce resource. As we expect that a far smaller fraction of the similarly sized potential silica sand volumes will be exploitable, we conclude that Dutch silica sand resources are limited indeed and should be carefully managed.

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Although the authors adhere to its basic principles, this study does not formally comply with the current reporting conventions (Anonymous, 2001, 2008; see also Anonymous 2004b). Our results are not to be used for the purpose of (a) informing investors or potential investors and their advisers or (b) satisfying regulatory requirements.

This paper is dedicated to the memory of Gerrit-Jan Evers († 30 November 2009).

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Bijlage 6 – Nadere toelichting modellen

Maljers, D., Stafleu, J., Van der Meulen, M.J., Dambrink, R.M., 2015. Advances in constructing regional geological voxel models, illustrated by their application in aggregate resource assessments. Netherlands Journal of Geosciences 94: 257-270. doi:10.1017/njg.2014.46

Netherlands Journal of Geosciences — Geologie en Mijnbouw page 1 of 14 doi:10.1017/njg.2014.46

Advances in constructing regional geological voxel models, illustrated by their application in aggregate resource assessments

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Abstract

Aggregate resource assessments, derived from three subsequent generations of voxel models, were compared in a qualitative way to illustrate and discuss modelling progress. We compared the models in terms of both methodology and usability. All three models were produced by the Geological Survey of the Netherlands. Aggregate is granular mineral material used in building and construction, and in this case consists of sand and gravel. On each occasion ever-increasing computer power allowed us to model at a higher resolution and use more geological information to constrain interpolations. The two oldest models, built in 2005 and 2007, were created specifically for aggregate resource assessments, the first as proof of concept, the second for an online resource information system. The third model was derived from the ongoing multipurpose systematic 3D modelling programme GeoTOP. We used a study area of 40 × 40 km located in the central Netherlands, which encompasses a section of the Rhine-Meuse delta and adjacent glacial terrains to the north. Aggregate resource assessments rely on the extent to which the occurrence and grain size of sand and gravel are resolved, and on proper representation of clay and peat layers (overburden and intercalations) that affect exploitability. Average model properties (e.g. total aggregate content) are about the same in all three models, except for a difference resulting from converting older lithological classifications to the current one. This difference illustrates that data selection and preparation are paramount, especially when dealing with quality issues. Generally speaking the results of the aggregate resource assessments are consistent and satisfactory for all three models, provided that they are judged at the appropriate scale. However, the assessments based on GeoTOP best approach the desired scale of use for the aggregates industry; in that sense progress was significant and each model was a better fit for the purpose.

Keywords: Netherlands, 3D modelling, aggregates, geostatistics, resource assessment

Introduction

Building and construction require bulk amounts of aggregate (granular mineral material), produced from natural sand, gravel or solid rock resources. The Netherlands is one of the most densely populated nations in the world, with very high land use intensity. More than in most other countries, aggregates extraction interferes with existing or planned land use, and is often controversial. Because of this, access to Dutch aggregate resources is considered in integral spatial planning, rather than being secured through some specific minerals policy instrument (e.g. production planning; van der Meulen, 2005; van der Meulen et al., 2007a).

Integral spatial planning is based, amongst other criteria, on the evaluation of land use potential, and in the case of aggregates extraction it is obviously resource presence and quality that need to be considered. On regional to national scales, such information is usually provided by geological survey organisations. Since 2005, aggregate resource assessments made by the Geological Survey of the Netherlands have been based on voxel models, voxels being attributed volume cells in a rectangular 3D grid (3D pixels). So far, three such assessments have been carried out. The first two have national coverage (van der Meulen et al., 2005, 2007b; TNO, 2014a) and the third is derived from the Survey's ongoing multipurpose national 3D modelling programme GeoTOP (Stafleu et al., 2011, 2012). All three models are primarily based on borehole data. Progress has been made in the extent to which additional soft data have been taken into account, such as lithostratigraphic interpretations, geological map data and lithofacies concepts. In addition to that,

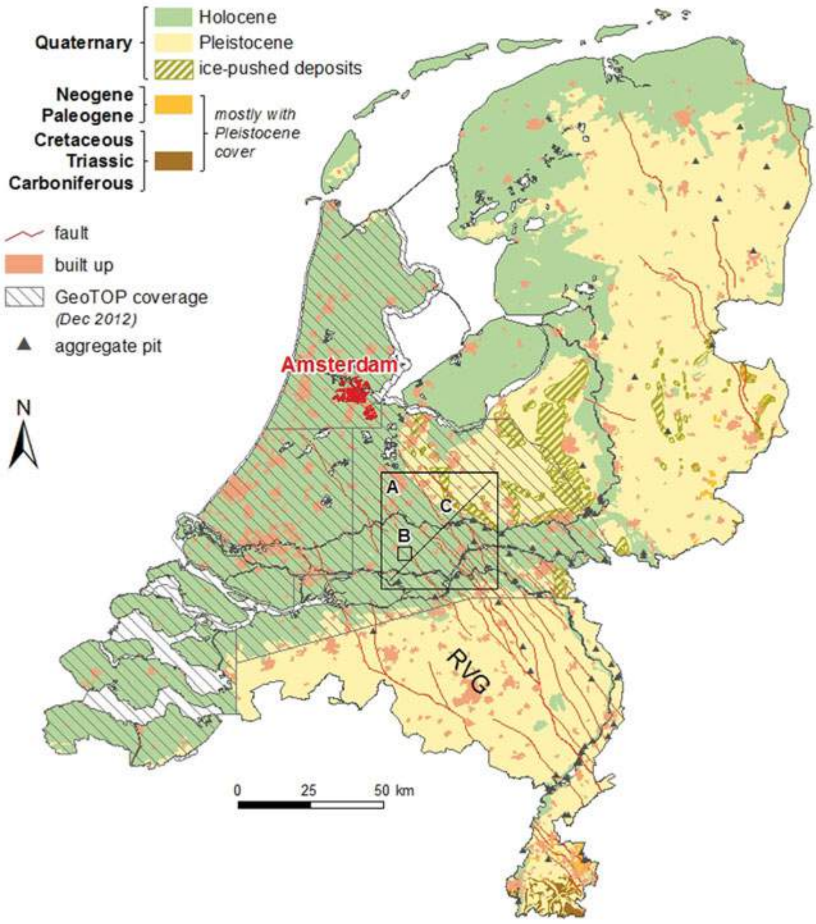

Fig. 1. Geological map of the Netherlands showing the location of the study area (A) and the proportion of the country with GeoTOP coverage (other models referred to in the text are nationwide). The study area is located in GeoTOP Rivierengebied (see text for explanation). The area marked (B) is discussed in detail; the cross-section line (C) refers to Fig. 2. RVG, Roer Valley Graben.

ever-increasing computer performance enabled us to produce each new model at a higher resolution.

While our 3D models became evermore detailed and geologically realistic, the development and production costs of these models rose by approximately two orders of magnitude. Using aggregate resource estimation as a test case, the present contribution discusses the progress made in our modelling efforts from a geological perspective *(How geologically appealing was each model?)* balanced against the effort and application possibilities *(Did each improvement make the model better fitted for the purpose?)*. As we aim to qualitatively describe actual progress in 3D modelling, we left the voxel models as they were when they were constructed. We rechecked and fine-tuned our resource calculations on the basis of the three models to achieve as much consistency as possible for our comparisons.

Although the authors adhere to its basic principles, this study does not formally comply with the current reporting conventions (Anonymous, 2001, 2008; see also Anonymous, 2004). Our results are not to be used for the purpose of (a) informing investors or potential investors and their advisers or (b) satisfying regulatory requirements.

Geological setting

Our study area, 40 × 40 km, is located in the central Netherlands and includes a section of the Rhine-Meuse delta and adjacent glacial terrains (Fig. 1). For the reasons outlined below the area is particularly suited for the evaluation at hand. It is large enough to include all relevant features to evaluate aggregate resource and produce resource statistics, and small enough to oversee and illustrate the differences between the models. Our primary comparisons were made down to 30 m below the surface, as aggregate extraction usually does not exceed this depth.

The Pleistocene in the delta area in the depth range of interest consists mainly of fluvial deposits of the rivers Rhine and Meuse (Waalre, Stramproy, Sterksel, Urk and Kreftenheye Fms; Busschers et al., 2005, 2007; all stratigraphic units cf. de Mulder et al., 2003; Fig. 2). The units vary lithologically and in fluvial style, which is ultimately controlled by the tectonics and hydrology of the Rhine and Meuse catchment areas, base-level variation and climate (especially through glaciations; Berendsen & Stouthamer, 2000; Busschers et al., 2005, 2007; Gouw, 2007; Gouw & Erkens, 2007). The dominant lithology is medium to coarse, occasionally gravely sand, but clay also occurs, especially in the older units. The sequences are generally coarsening upward.

During the penultimate (Saalian) ice age, the northeast corner of the study area was overridden by an advancing ice sheet. An ice-pushed ridge was formed (the Utrechtse Heuvelrug), of which the sandr fans (Drente Fm) interfingered with the fluvial systems that persisted in the south (Kreftenheye Fm). The

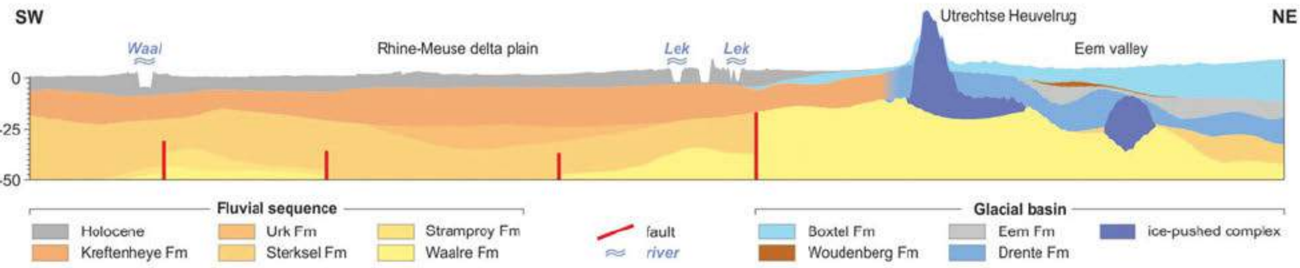

Fig. 2. Cross-section through the study area based on DGM (Gunnink et al., 2013; see text for explanation). For location see Fig. 1.

ice-scooped basin behind the Utrechtse Heuvelrug, the Gelderse Vallei, was filled initially by fluvio-glacial and proglacial deposits (Drente Fm). During the Eemian highstand the area was inundated by the sea, as evidenced by a body of shallow marine clays that is present at depths between 10 and 25 m, followed by coastal peat (Eem and Woudenberg Fms, respectively). At the beginning of the Weichselian ice age, sea level dropped and fluvio-glacial sedimentation resumed (Boxtel Fm).

Glacial desert conditions in latest Weichselian/earliest Holocene times led to widespread aeolian deposition of fine sand ('cover sands': Boxtel Fm, Wierden Mbr). The ensuing warming phase resulted in a transition from hitherto braided to meandering rivers in the delta area, as evidenced by a layer of latest Pleistocene to earliest Holocene floodplain clays (Kreftenheye Fm, Wijchen Bed). Eventually, postglacial rising sea and groundwater levels led to the formation of a peat layer that progressively covered the late glacial surface in an upslope/eastward direction, reaching the west of the study area between 8000 and 7000 yr BP (Nieuwkoop Fm, Basisveen Bed; Vos et al., 2011). This phase was followed by fluvial aggradation, characterised by sandy channel belts amidst clayey and occasionally peaty flood basin deposits (Echteld Fm and Nieuwkoop Fm, Hollandveen Mbr, respectively). Natural sedimentation ended by mediaeval times, when dikes were first established throughout the area (e.g. van der Meulen et al., 2007c).

Assessing aggregate resources

In the delta, Pleistocene sand layers and the overlying Holocene channel belts or other fluvial sand bodies constitute the aggregate resource, and Holocene flood basin fines make up the overburden that has to be removed before sand can be extracted. Intercalations of Pleistocene fluvial clays, where present, may inhibit aggregate dredging. The ice-pushed ridge and associated sandr deposits make for excellent aggregate resources that, in fact, are not accessible because the area has protected nature status. Sands in the glacial basin should in principle be extractable down to the Eemian clays and overlying peat, but are generally too fine-grained for any application except filling sand.

Aggregate resource potential is largely determined by grain size, which – after lithology – is the most important property attribute of any aggregate resource model. As a rule of thumb, the coarser the sand, the better it is as an aggregate resource, at least for applications such as concreting. Obviously, the industry has specific standards for aggregates, but these can only be applied if grain-size distribution data are available. Such data are sparse in our databases, so we have to work with grain-size classes and descriptors such as median grain size, which only allow us to approximate the yield and quality when working on regional to national scales (van der Meulen et al., 2005). Based on such data, we currently distinguish between three aggregate resource categories: all sand and gravel, medium to coarse aggregate, and coarse aggregate (Table 1; TNO, 2014a). In terms of the extractive industry, the latter two categories refer to concreting and masonry sand, and concreting sand (both including gravel).

Equally important is to accurately determine overburden thickness: the thinner the better, with a threshold value of about 5 m for onshore sites (van der Meulen et al., 2005). The main challenge in the delta area is to adequately capture the heterogeneity of the Holocene Rhine and Meuse deposits. This concerns the heterogeneity of flood basin deposits (Bos & Stouthamer, 2011), and most particularly the channel belt network (Fig. 3): in the study area, the overburden is likely to be thinner than 5 m on top of channel belts and thicker in between. Such complexity makes this area very much suited for the present evaluation. Finally, an exploitability criterion was applied to account for clayey and peaty intercalations within the aggregate resource: once the cumulative thickness of such intercalations exceeds a threshold of 2 m, aggregates further down are discarded as unexploitable.

Material and methods

Model descriptions

The Survey's first nationwide voxel model was built specifically to test the application possibilities for aggregate resource assessment purposes (van der Meulen et al., 2005). The model, hereafter referred to as the Aggregates model, has voxel dimensions of 1000 × 1000 × 1 m, attributed with the shares

Table 1. Lithoclasses of sand and gravel used in this study and their translation to aggregate yields.

			Aggregate yield (%)		
Lithology	Lithoclass	Median grain size	A	M	C
Sand	Extremely fine	$\geq 63 < 105$ μm	100	–	–
	Very to moderately fine	$\geq 105 < 210$ μm	100	50	–
	Moderately to very coarse	$\geq 210 < 420$ μm	100	100	50
	Extremely coarse sand	$\geq 420 < 2000$ μm	100	100	100
Gravel		$\geq 2 < 63$ mm	100	100	100

A, all sand and gravel; M, medium to coarse aggregate; C, coarse aggregate.

of the lithoclasses clay (including loam), peat (and gyttja), sand and gravel (subdivided according to the grain-size criteria in Table 1), and other material. Its successor had voxels of 250 × 250 × 1 m that are similarly attributed. Resource maps based on that model can be accessed interactively at http://www.delfstoffenonline.nl ('minerals online', in Dutch, van der Meulen et al., 2007b); this model will hereafter be referred to as the Delfstoffen Online model. Both models were constructed down to 50 m below the surface.

GeoTOP, a systematic detailed 3D modelling programme, was initiated by the Survey in 2006 to provide a uniformly constructed, multipurpose framework for subsurface information, serving as an easily accessible information source for any activity in, or interacting with, the subsurface, e.g. building and construction, ground water management, surface mineral resource assessments and land use planning (Stafleu et al., 2011). The programme produces model blocks corresponding roughly to a province in areal extent, having started in the extreme southwest of the country and moving northwards since (Fig. 1). The general plan is to first finish the Holocene coastal and fluvial lowlands (more than half of which are currently covered) and then continue with the Pleistocene terrains that make up the larger part of the southeastern half of the country. GeoTOP has voxel dimensions of 100 × 100 × 0.5 m and is constructed down to 30 m below surface level.

Every province-sized block takes about two years of construction time, the first of which is dedicated to data preparation and geological concept development, and the second to the actual modelling, including quality control, producing the accompanying documentation and delivery. The GeoTOP model Rivierengebied, in which the study area is located, was delivered by the beginning of 2012, covering the entire Rhine-Meuse delta and adjacent Pleistocene terrains.

After finishing a GeoTOP area updates can be made to www.delfstoffenonline.nl by replacing results based on the original Delfstoffen Online model with GeoTOP-based results. For that purpose, the resulting GeoTOP model is scaled up to 250 × 250 × 1 m to fit within the Delfstoffen Online model. For the present analysis, however, the high-resolution (not the upscaled) results were used. On finalisation of the GeoTOP

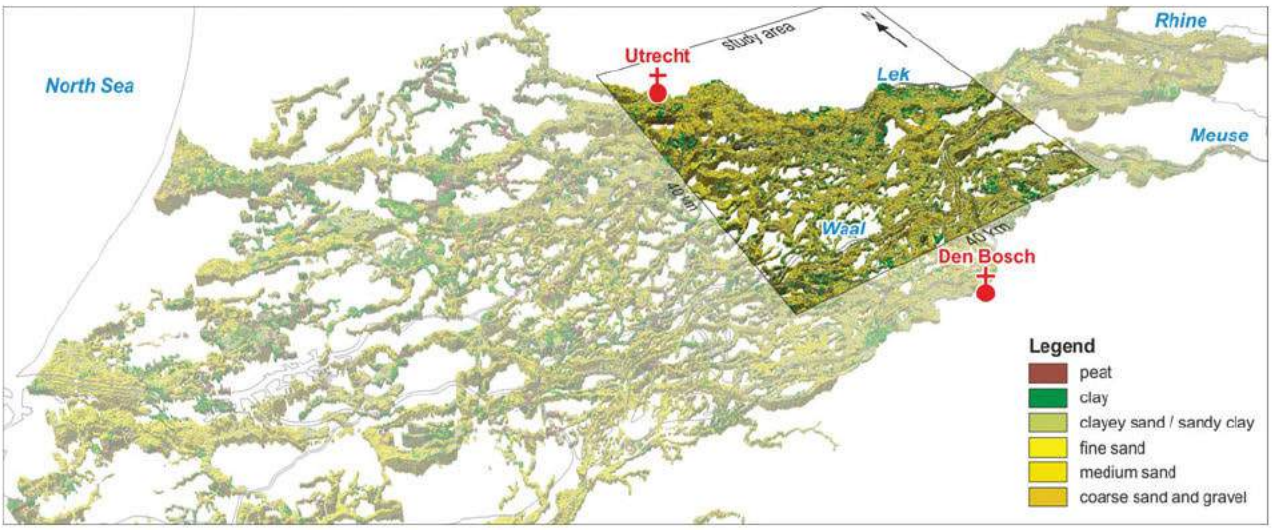

Fig. 3. Representation of the channel belts of the Rhine-Meuse delta in GeoTOP Rivierengebied and Zuid-Holland. The main lithology in the belts is sand, but clay and peat also occur and affect the prospectivity and exploitability of (underlying) aggregate resources. The lithoclasses shown in the legend are the standard GeoTOP lithoclasses instead of the ones used for resource assessment purposes (see text for explanation).

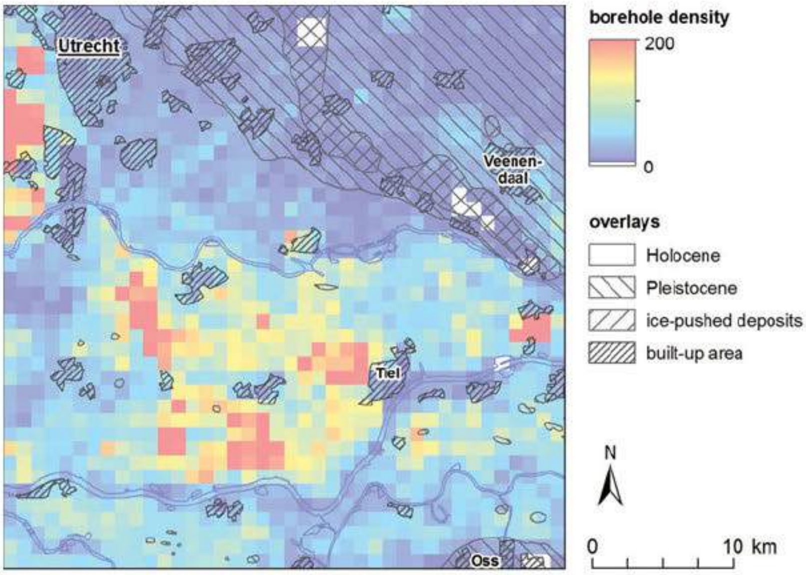

Fig. 4. Current data distribution in the study area, see Fig. 1 for geographical and geological reference. The Holocene floodplains are clearly better sampled than the Pleistocene terrains, which is largely because of the additional boreholes of Utrecht University used for GeoTOP modeling (see text for explanation). The size of the grid cells is 1 km.

programme, the results on www.delfstoffenonline.nl will be converted to the highest resolution.

Hard data

The borehole data used for all three models were retrieved from DINO, the national repository of subsurface data developed and maintained by the Geological Survey of the Netherlands (TNO, 2014b). Sand descriptions usually include estimated or measured median grain sizes, as either a class (extremely fine, very fine, etc.) or a discrete value (M63: the median grain size of the sand fraction). Gravel occurrences or admixtures are described in similar ways, although quantifications or classifications occur somewhat less frequently.

DINO currently contains data for 452,000 boreholes. This number includes 326,000 survey boreholes, which are fairly consistent in terms of their description and classification, even though classification systems varied or evolved over time. The remaining 126,000 were supplied by third parties, which vary considerably in the latter respect, and moreover it cannot always be straightforwardly determined what classification was used. Our modelling efforts are all therefore preceded by a data preparation step in which choices are made as to how various older/non-standard classification systems translate to the one currently used (Anonymous, 1989, 1990).

The study area currently encompasses 23,850 boreholes in DINO (Fig. 4). Since DINO was launched, the number of boreholes it contains has grown by about 3% per year, so the Aggregates and Delfstoffen Online models were based on largely the same data set (about 13 boreholes/km^2 on average at the time). For the GeoTOP modelling of the Rivierengebied, an extra 104,000 borehole descriptions were made available by Utrecht University, 57,605 of which are located in the study area. These data have been collected since 1959 by students of physical geography, amounting to a unique data set in terms of consistency, density and quality, covering the entire Rhine-Meuse delta (Berendsen & Stouthamer, 2000). The Utrecht University boreholes generally penetrate floodbasin deposits and the upper centimetres of sand (either channel belt or Pleistocene substrate), and in the context of the present analysis contribute to the characterisation of the overburden layer and the positioning of the channel belts (Berendsen & Stouthamer, 2001; Cohen & Stouthamer, 2012). Finally, 1139 boreholes were made available by the province of Utrecht, amounting to a total of 82,594 boreholes (52 boreholes/km^2, Fig. 4).

Soft data

Besides working at ever-increasing resolutions, the extent to which interpolation routines were geologically constrained increased. Lithology and associated properties are geologically confined at various scales: from within lithostratigraphic units (which our Survey defines on the basis of macroscopically observable rock characteristics), down to their constituents (ranging from stratigraphic members to single facies units).

The more geological features are represented in the model, the more detailed and geologically appealing it will be, and the better it will presumably predict aggregate prospectivity. We currently achieve this by using available geological information deterministically, e.g. stratigraphic concepts and geological maps. In the Aggregates model this approach has not yet been used and all boreholes were interpolated within the 3D model space without considering their lithostratigraphical context, so the extent to which that model is realistic is primarily attributable to data density (and of course quality).

In the Delfstoffen Online model, interpolation was confined to the lithostratigraphic units of the Digital Geological model (DGM; Gunnink et al., 2013). DGM is a 3D geological raster model consisting of a stack of grids representing the tops and

Table 2. Overview of the model properties.

	Aggregates model	Delfstoffen Online model	GeoTOP
Voxel dimensions	**1000 × 1000 × 1 m**	**250 × 250 × 1 m**	**100 × 100 × 0.5 m**
Geological framework	N/A	DGM	Refined DGM, Holocene subdivision
Modelling technique	Linear kriging	Punctual kriging	Sequential indicator simulation
Search neighbourhood	Single	Single	Per geological unit
Variogram model	N/A	Single	Per geological unit

For modelling techniques see Goovaerts (1997) and Chilès & Delfiner (2012). The interpolations were performed in the commercially available software package Isatis® by Geovariances.

bases of Quaternary and Neogene formations, based on a set of 16,500 high-quality, stratigraphically interpreted borehole descriptions. The Holocene, however, while divided into two formations in the study area, is represented by a single composite unit (Fig. 2).

A refined version of DGM, based on all available boreholes instead of the aforementioned subset, is used in the production of GeoTOP and additional detail was added. The Holocene composite unit in the study area was subdivided into its constituents: Echteld Fm (fluvial), Nieuwkoop Fm, Basisveen Bed and Hollandveen Mbr (see above). Within the Boxtel Fm, where possible, we mapped the Wierden Mbr (see above), Singraven Mbr (brooke facies) and Kootwijk Mbr (aeolian drift). Finally, fluvial Holocene channel belts, mapped by Berendsen & Stouthamer (2001) and Cohen & Stouthamer (2012), were incorporated into the model as separate entities to further constrain interpolations. These channel belts are mapped at a scale of 1:100.000, the smaller ones being less wide than the grid resolution of 100 m. Mapping originally relied on the combination of augering and field geomorphology. Following the approach of Berendsen (2007), considerable improvements in mapping accuracy have been achieved by using Actueel Hoogtebestand Nederland (AHN). AHN is a national high-resolution elevation model based on airborne laser altimetry, which reveals channel belts as subtle elevations with respect to the more compactable floodplain fines.

The mapped outline of channel belts acts as a lateral boundary in the interpolation step of GeoTOP and is kept constant throughout the modelling process. The top and base of the channel belts are constructed using borehole data. The voxels within the channel belts are filled using only lithological information from boreholes within the channel belt, and the voxels outside this outline are filled using only boreholes outside the belt. In this way the generally better sampled floodplain fines do not 'dilute' the sandier channel belts, or vice versa.

Modelling techniques

Each of the three models was constructed with a different interpolation technique (Table 2), but the outputs were processed in the same way, i.e. by applying resource and exploitability criteria to individual voxel stacks down to certain desired depths. The same criteria were used to produce map output of total and exploitable resource amounts for all three models (Fig. 5). Linear kriging, i.e. ordinary kriging with a linear variogram, was used for the interpolation of the Aggregates model (van der Meulen et al., 2005). As we were only interested in the estimated values, the slope of the variogram is not requested by the algorithm, therefore the only way to account for geological variability while using this technique is in setting the search neighbourhood, which determines to which distance samples will contribute to the estimation for a voxel. Punctual kriging was used for the Delfstoffen Online model, using a single search neighbourhood and variogram for the entire model space, i.e. the same ones irrespective of the DGM unit. A variogram describes the spatial distribution and structure of the samples: it weighs the contribution of samples within the search neighbourhood (in general, the closer the sample, the greater its weight).

For GeoTOP we transformed every description interval into an indicator, i.e. the discrete descriptor 'lithoclass' (Fig. 5). Sequential indicator simulation (SIS) was used for the interpolation step, using a search neighbourhood and variogram model per geological unit, resulting in voxels having a most likely lithoclass estimate. The final model product is averaged from 100 equiprobable simulations using the method described by Soares (1992; Stafleu et al., 2011, 2012). Note that the standard GeoTOP lithoclasses described by Stafleu et al. (2011) differ from the ones we use for aggregate resource assessments (Table 1), so a different GeoTOP variant was created for this particular application, using the standard workflow with adapted settings.

Resource maps are derived from voxel models by the analysis of vertical cell stacks. Total resource maps are generated by summing voxels which meet the selected resource criterion down to the desired exploration depth. Exploitable resource maps are generated by considering the thickness of an overburden or intercalation layer of clay and/or peat, discarding aggregates below such layers if set thickness thresholds are exceeded.

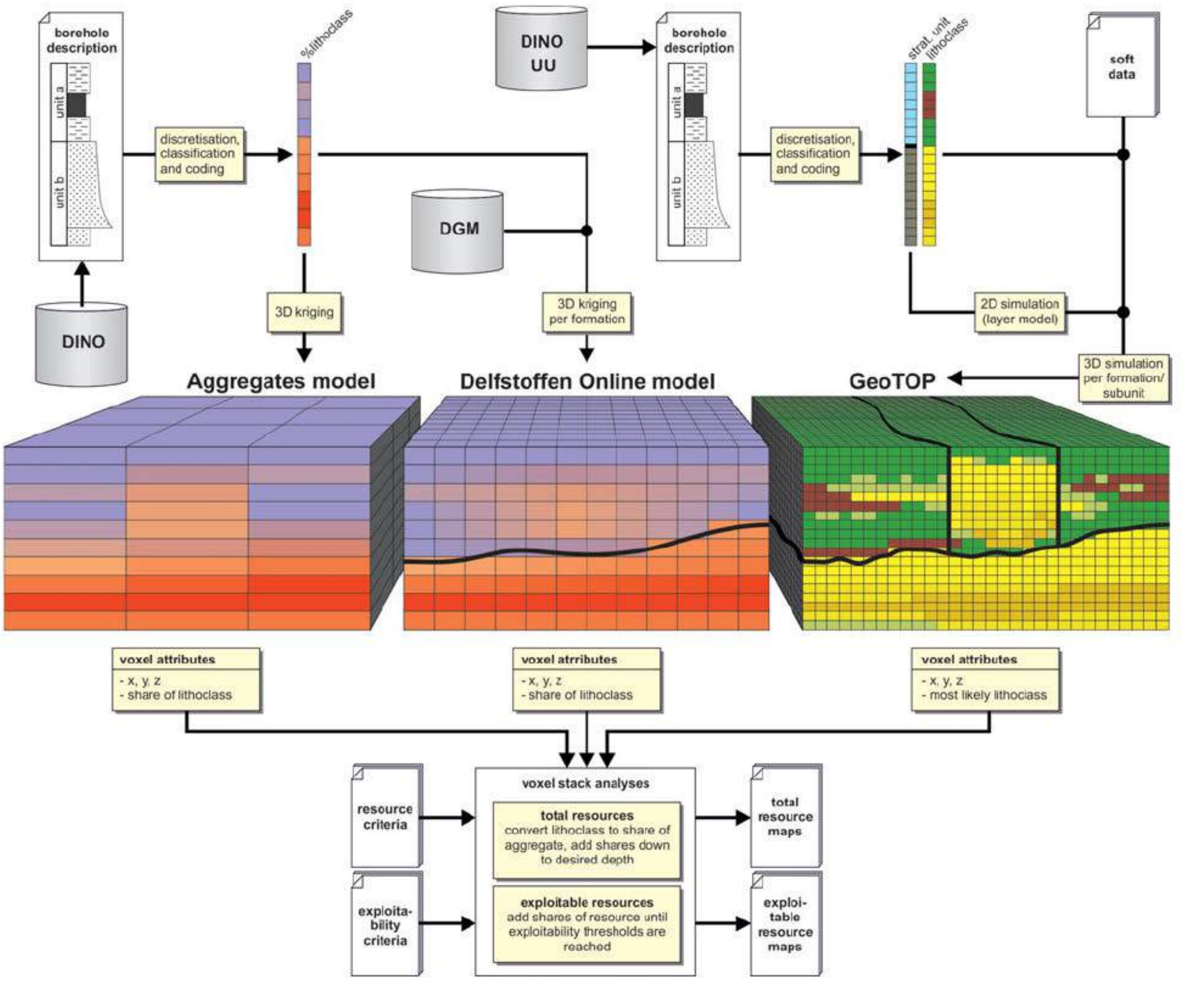

Fig. 5. Generalised workflows for the Aggregates, Delfstoffen Online and GeoTOP models. Resource criteria refer to Table 1. General principles are outlined in the text and details can be found in Table 2 (model parameters), van der Meulen et al. (2005, 2007b) and Stafleu et al. (2011, 2012).

Results

Fig. 6 shows total and exploitable resources of coarse sand and gravel in the study area as predicted by the three models. The most obvious difference, apart from resolution as such, is the extent to which geological features are distinguishable, especially in the exploitability maps, which are most susceptible to geological variation. Only national-scale features appear in the Aggregates model, most notably the ice-pushed ridges, the Roer Valley Graben system and the general difference between Holocene and Pleistocene terrains in the northwest and southeast of the country, respectively (see Fig. 1 and van der Meulen et al., 2005). The dimensions of these phenomena exceed those of the study area, where only the differences between the Rhine-Meuse Delta, the Utrechtse Heuvelrug ridge and the hinter-lying glacial basin in the northeast stand out. As proof of concept, the aggregate resource assessment based on the Aggregates model was only successful in predicting general areas of higher prospectivity, which correspond to concentrations of extraction sites. This assessment is clearly not suitable for site-scale assessments and was never used for that purpose.

The assessment based on the Delfstoffen Online model retains these general features, and the exploitability map better reflects the heterogeneity of the delta plain. However, while the channel belts that mainly cause this heterogeneity are more or less identifiable, they are rather patchily represented. The same map derived from the GeoTOP model on the one hand shows more continuous channel belts, but on the other also a more heterogeneous pattern in between, in the flood basins, which is not or hardly present in Delfstoffen Online. Fig. 7 shows both effects in more detail, in a cross-section perpendicular to the belt of the river Linge, a minor Rhine distributary. In the Delfstoffen Online cross-section, floodplain and channel deposits are 'mixed' to the extent that the channel is not recognisable as an entity, neither in cross-section, nor on the map. In GeoTOP,

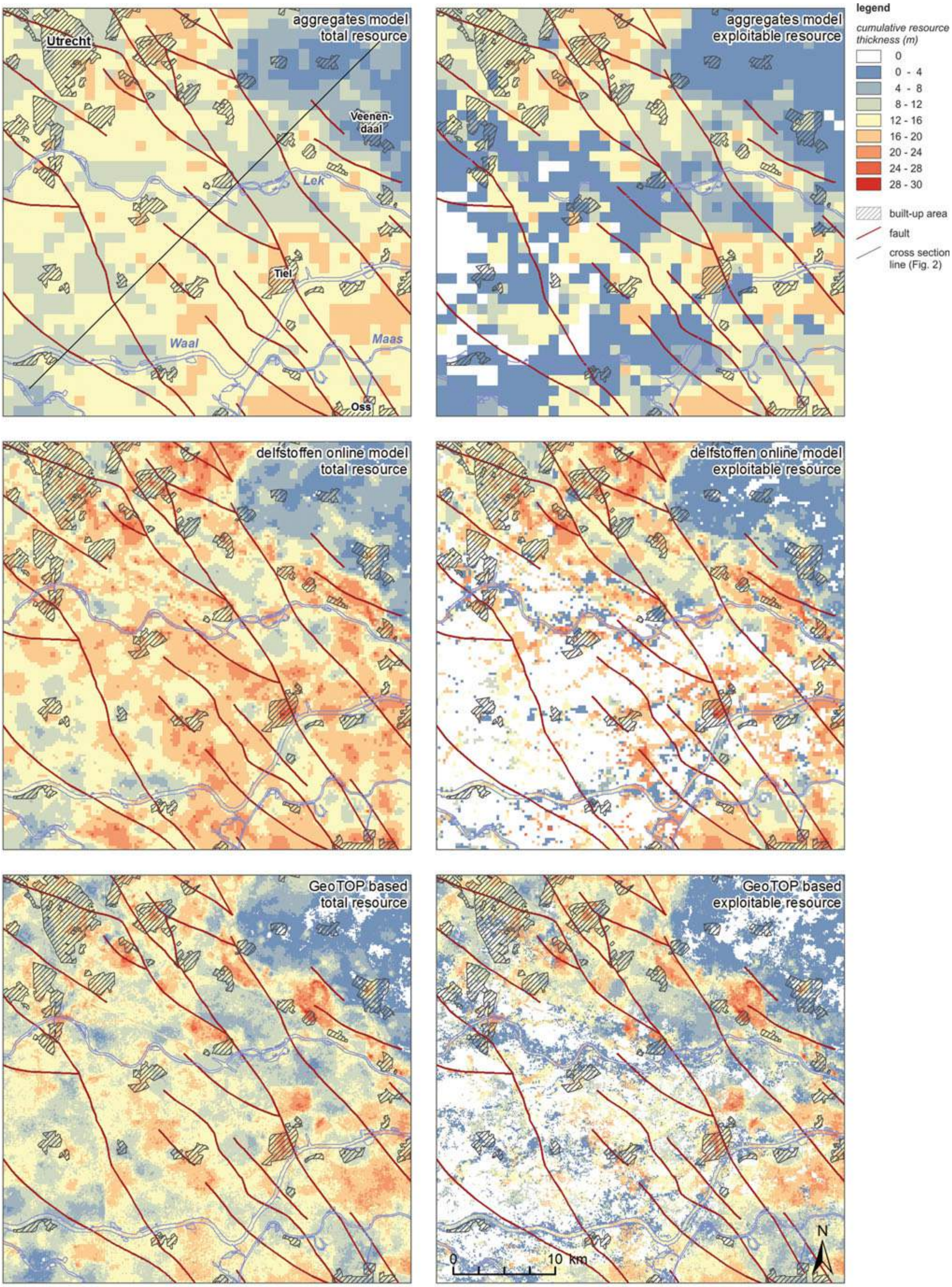

Fig. 6. Total (left column) and exploitable (right column) coarse aggregate resources in the study area down to 30 m below the surface, according to the Aggregates model (upper row), Delfstoffen Online model (middle row) and GeoTOP (lower row).

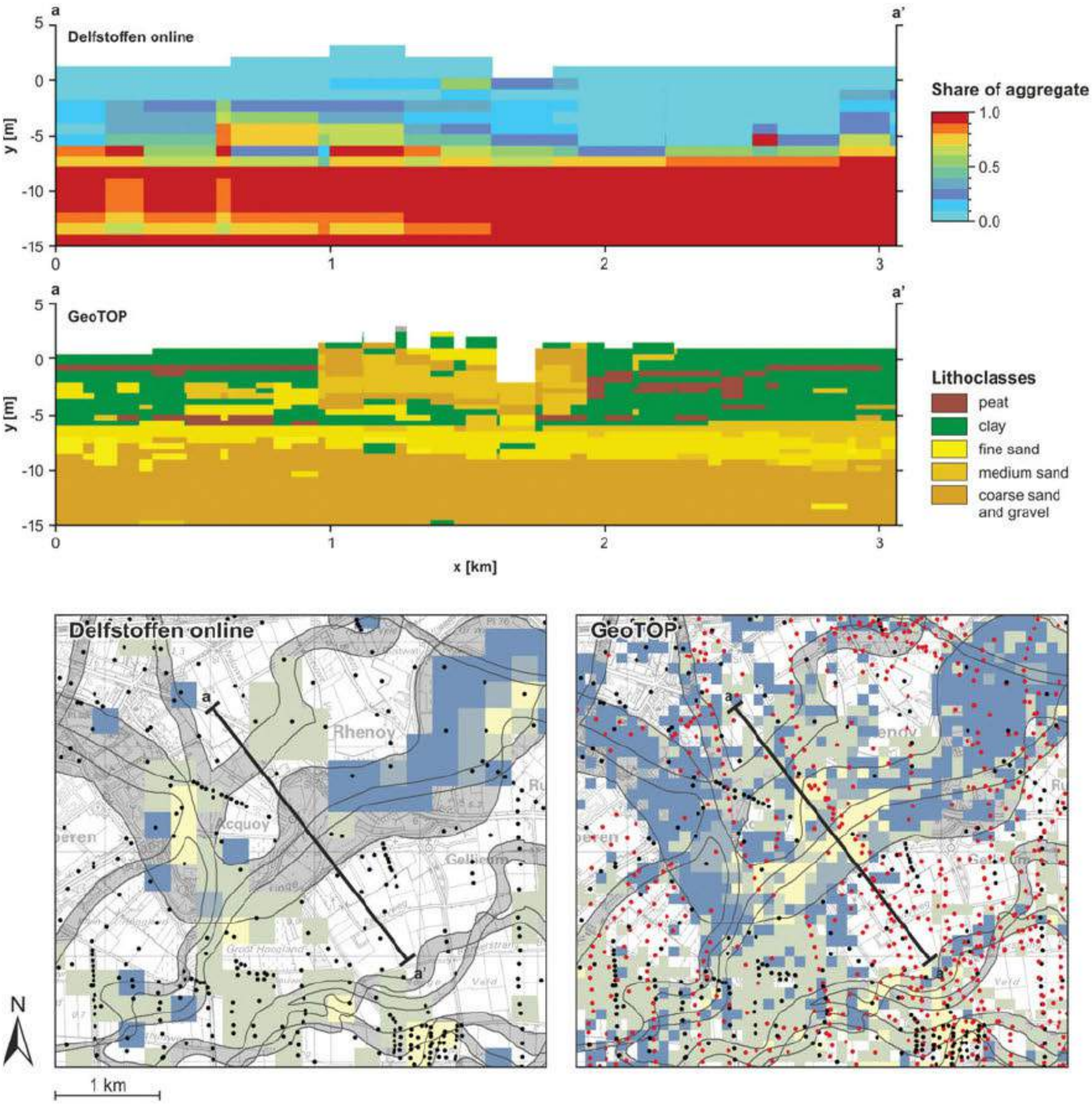

Fig. 7. Cross-section through the channel belt of the river Linge based on the Delfstoffen online model (upper panel) and on GeoTOP (lower panel). The upper panel shows the share of aggregate (blue, low percentages; red, high percentages); the lower panel shows the discrete lithoclasses. The reference datum for both cross-sections is NAP (Dutch Ordnance Datum). The extent to which the channel belt is resolved is also evident from the location maps, which show exploitable resource of coarse aggregate for both models. The colour scale used in the maps is as in Fig. 6; grey shading, channel belts (Berendsen & Stouthamer, 2000); black dots, boreholes in DINO; red dots, boreholes obtained from Utrecht University.

however, the Linge channel belt is clearly represented, as is a smaller one to the north.

A second important difference is in the resource amounts: the maps in Fig. 6 derived from the Delfstoffen Online model are clearly 'redder', indicating higher resource amounts than those from the other two models. Fig. 8, a graph of bulk total and exploitable resource volumes in the study area, shows that Delfstoffen online contains some 20% more resource in comparison with the other two models. Fig. 8 also shows that the Delfstoffen Online predicts lower exploitability down to 30 m than the other two.

Figs 9 to 11 show the dependency of total and exploitable resource estimates down to 30 m below the surface on grain-size category in Delfstoffen online and GeoTOP (as the Aggregates model did not have multiple grain-size categories), expressed in resource maps and resource volumes. The difference is primarily in the share of coarse aggregate in the total volume of all sand and gravel: the cumulative volume of all aggregates is the same and the medium category differs only slightly; exploitable resources vary proportionally but overall exploitability is higher for GeoTOP (Fig. 11). The integrity of the channel belt network, again, is even more visible in the upper panel of Fig. 10, which

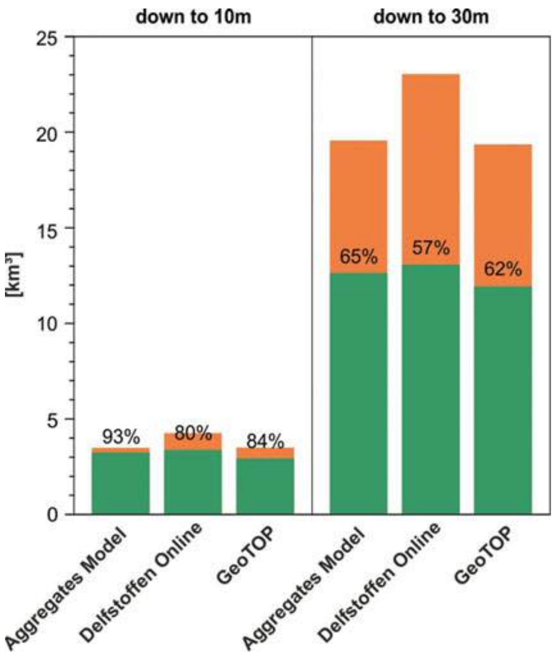

Fig. 8. Cumulative total (in orange) and exploitable (in green) coarse aggregate resources down to 10 and 30 m below the surface according to the Aggregates, Delfstoffen Online and GeoTOP models. For example, the Delfstoffen Online model predicts a total amount of 23 km^3 down to 30 m below surface level, of which 13 km^3 or 57% is exploitable.

show the exploitability of all sand and gravel regardless of grain size: patchy for Delfstoffen Online versus more continuous channel belts in GeoTOP, alternating with more heterogeneous flood basins.

Discussion

Aggregate resource estimates provide a common ground for comparisons between three successive generations of voxel models produced by the Geological Survey of the Netherlands, which differ in terms of purpose, resolution and attribution. The different methods used for the three models share the general principle that the proportions of lithoclasses in the model output correspond to those in the input data. The boreholes used for resource characterisation were virtually the same, as the Utrecht University dataset primarily covered the top layer, i.e. the overburden. The observed differences in coarse aggregate resource amounts can therefore only arise from choices during the data preparation step. More specifically, two seemingly arbitrary choices made when mapping older sediment classifications to the grain-size categories we use for resource assessment purposes have affected the outcomes to a significant extent, at least for the coarsest resource category.

Delfstoffen Online predicts lower exploitability down to about 30 m than the Aggregates model, even though the models are similarly attributed and have the same vertical resolution. This means that, on average, exploitability thresholds are reached at shallower depths in Delfstoffen Online, which suggests that clay and peat are better confined to the overburden layer, just as can be expected from using DGM in the interpolation step.

GeoTOP predicts higher exploitability than Delfstoffen Online because better resolved features such as the channel belt network provide more 'access' to the underlying resource (as demonstrated in detail in Fig. 8). The similarity in total sand and gravel volumes in Delfstoffen Online suggests that the area was already well enough sampled without the extra Utrecht University boreholes to predict averaged subsurface properties. However, while these boreholes did not appear to add to averaged properties, they clearly enabled us to better capture the 3D geometry of the channel belts.

The answer to the question whether each next generation in voxel modelling was worth the investment, based on the present evaluation, is 'yes', for a simple reason. While we considered an area of 40 × 40 km, site pre-prospection is obviously done at much smaller scales; the largest Dutch aggregate pit has a surface area of about 4 km^2. The Aggregates model was clearly unsuitable for that purpose. Delfstoffen Online was a major improvement, but its patchiness presents a problem. If, for example, the model would be consulted between two patches of high prospectivity that should actually have been connected, then the area could theoretically be discarded for wrong reasons. Hence, the extra geological constraints used in GeoTOP modelling improved the results in a way that is relevant to the application at hand. More obviously, additional data, which enable better characterisation of the flood basins, improved the output for similar reasons. More generally speaking, our progress in voxel modelling is expressed in a better prediction of subsurface properties. Average properties are about the same in all three models; variation and heterogeneity became better represented over time.

Conclusions

Progress made in our geomodelling efforts has largely been enabled by increasing computer power and project budget. This allowed us to deploy evermore elaborate modelling workflows, increasing the resolution at which we model, and including more geological data to better constrain the interpolations. The present paper essentially compares model realisations at three different scales. In a formal geodetic perspective it is not fair (or even correct) to compare the models as we did: at the same scale. The specific reason why GeoTOP is better than the previous models that it is the best fit for the purpose: it best approximates the desired scale for the application at hand.

In the future, the main delimiting factor for our geomodelling efforts will be data availability (van der Meulen et al., 2013). In that context, it is most relevant that the Geological

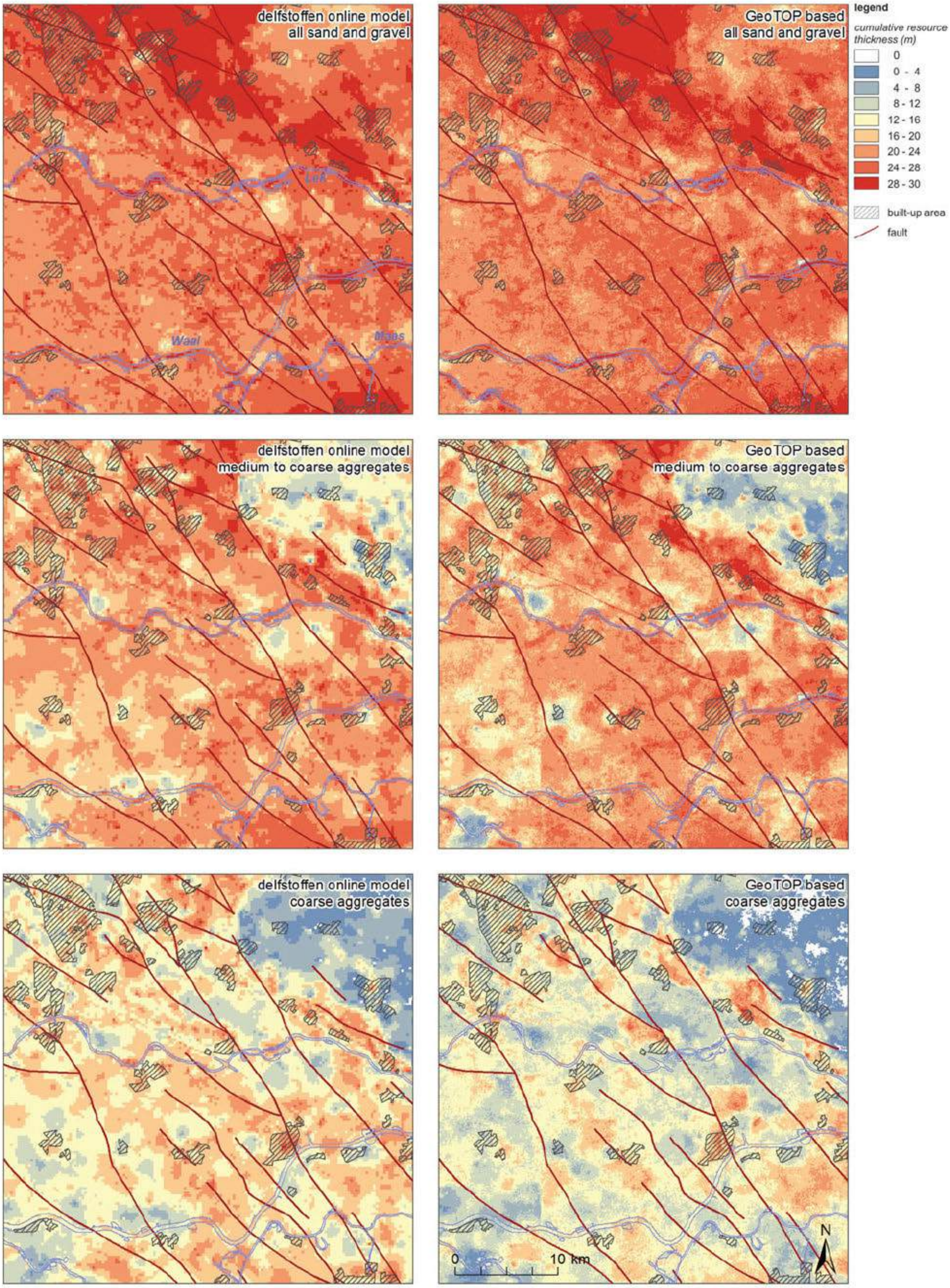

Fig. 9. Total resources of all sand and gravel (upper row), medium coarse aggregate (middle row) and coarse aggregate (lower row) down to 30 m below the surface, according to the Delfstoffen Online model (left column) and GeoTOP (right column).

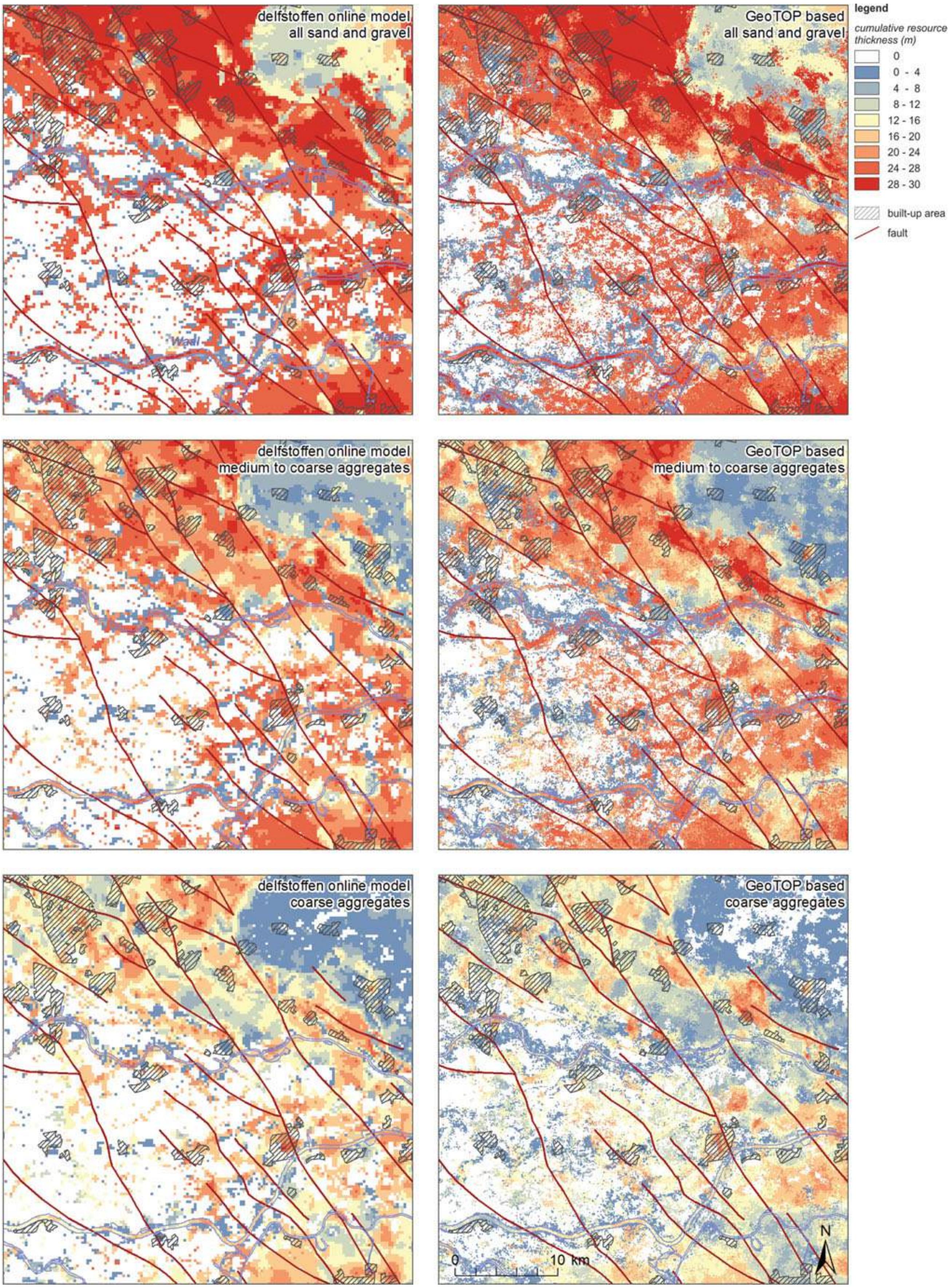

Fig. 10. Exploitable resources of all sand and gravel (upper row), medium coarse aggregate (middle row) and coarse aggregate (lower row) down to 30 m below the surface, according to the Delfstoffen Online model (left column) and GeoTOP (right column).

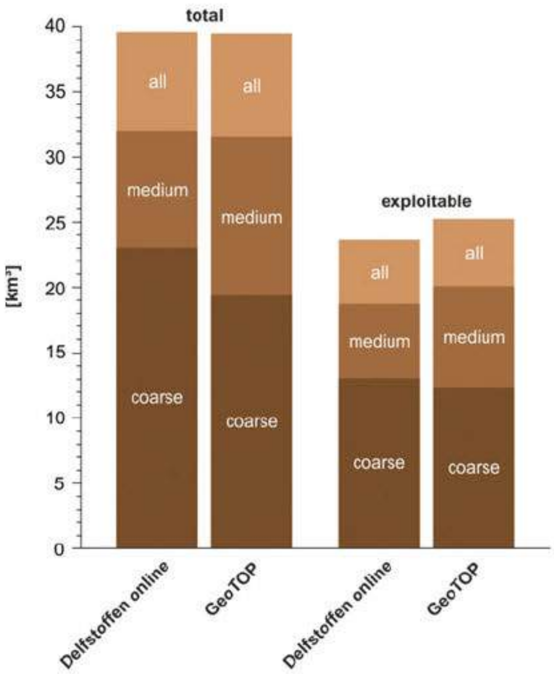

Fig. 11. Cumulative total and exploitable aggregate resources in the study area in three grain-size categories down to 30 m below the surface, calculated from the Delfstoffen Online and GeoTOP models.

Survey of the Netherlands is preparing for a new law on subsurface information in the Netherlands. Under this law, DINO will be upgraded to a key register for the subsurface, an official type of database in which the government uniquely stores data that is vital to its tasks. This upgrade is associated with a standardisation effort and the obligation of government bodies to feed and consult the register. This will raise the consistency and volume of subsurface data, and undoubtedly prove a sine qua non for further improvement of our subsurface models and all activities that use them, such as assessing aggregate resources.

There are two more general lessons to be learned from our analysis. The first is related to the management of geological information. Whilst the specifications, properties and outputs of the older models we assessed were retained, the modelling as such turned out not to be completely reproducible because this would require using vintage software as well as a 'frozen' excerpt of our database as it was at that time. Even though it did not present limitations to the present study, we recommend that special attention is paid to reproducibility, not only for systematically produced models such as GeoTOP, but also for one-off exercises conducted for proof of concept, contract research, etc. This will increase the reuse possibilities of geological information products in unanticipated situations (including the present study into modelling progress).

The second lesson is related to the fact that, while the highest-resolution model was best-suited for resource assessments, the oldest one has in fact not been invalidated (provided that it is used at the appropriate scale). The two orders of magnitude difference in investment between two basically useful models indicates that it is very important to thoroughly articulate the problem that is to be addressed by a subsurface modelling exercise.

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